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Pitout JDD, Church DL, Gregson DB, Chow BL, McCracken M, Mulvey M, Laupland KB (2007). Molecular epidemiology of CTXM-producing *Escherichia coli* in the Calgary Health Region: emergence of CTX-M-15-producing isolates. *Antimicrob. Agents Chemother.* 51: 1281-1286.

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*Full Length Research Paper*

# Assessing the farmers perception of climate variability and change: A case study of Miesso-Assebot Plain, Eastern Ethiopia

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**Assessment of farmers' perception and adaptation mechanisms at local level has enormous advantages in Ethiopia, where the driver of the economy is agriculture. This study was conducted to assess the perceptions of farmers to climate change and increased climate variability, and to identify the potential adaptation options. Most farmers noted an increase in temperature and decrease in precipitation in the last fifty years. The farmers' perception of increasing temperature was in accordance with the statistical climate data record; however, the farmers could not differentiate between consistent changes in climate and yearly rainfall fluctuation. Moreover, majority of the farmers were aware of frequent drought occurrence, shift in onset date and early withdrawal of rainfall. As a result, the farmers indicated decreased diversity of cultivated crops, changes in farming practices, new patterns of diseases, crop infestations with new weed species and frequent total crop failures. Furthermore, the majority of the respondents perceived water shortage, great loss of biodiversity and forest resources, and decline in soil fertility as the most serious impact of climate change. Use of different planting dates, on farm soil and water conservation, use of local and early maturing varieties were the major adaptation strategies practiced by farmers to mitigate climate change impacts at Miesso. However, production of drought tolerant cultivars with optimum maturity periods, introduction of new crops, varieties and crop management practices that go in line with the changing climate are recommended to offset climate change impacts on crop production at Miesso-Assebot plain, Eastern Ethiopia.**

**Key words:** Climate variability and change, perception, adaptation options, Miesso-Assebot Plain.

## INTRODUCTION

Climate change is rapidly emerging as one of the most serious threats to the totality of human existence.

Different studies revealed that global mean surface temperature will be increased by 1.4 to 5.8°C between

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1990 and 2100 which is expected to be a much more rapid rate of warming than during the 20<sup>th</sup> century (Gruza and Rankova, 2004; Majule, 2008). Majule (2008) reported that the average global precipitation was projected to increase but, at regional levels there will be both increase and decrease in intensity of rainfall ranging from 5 to 20°C. Globally, these projected higher temperature and variable precipitation levels will unequivocally reduce crop yields through direct effects as well as indirect impact by triggering insect pests, diseases and weeds (Gadgil et al., 1998). The threats to food security and sustainable growth of developing countries will be much higher as the extent to which the impacts will be felt depends on adaptive capacity of communities (Mendelsohn and Dinar, 2009; Mtambanengwe et al., 2012).

About 66% of the total area of Ethiopia falls within arid and semi-arid climatic zones of the country (MoA, 1998). Nevertheless, agriculture, which is highly sensitive to climate variability and change (Hellmuth et al., 2007; Thornton et al., 2006; Teshome et al., 2008), is the driver of the country's economy as it accounts for half of GDP and 80% of employment (MoARD, 2007). Climate variability, particularly rainfall variability and associated drought, and increased frequency of extreme events could make rainfed agriculture more risky and aggravate food insecurity in Ethiopia (Seleshi and Zanke, 2004; Stern, 2007; Conway and Schipper, 2011). Preliminary projections suggested that climate change can have a sizeable impact that ranges in the order of 7-8% of GDP loss per year in Ethiopia (UNDP, 2011). These will form a serious concern for both researchers and development planners in Ethiopia and elsewhere.

Moreover, in Ethiopia, the risks associated with change in climate patterns that smallholderface is believed to be due to low adaptive capacity of society and limited adaptation options of agricultural sector (Yesuf et al., 2008; Mengistu, 2011). Hence, the livelihood approach of a locality could provide a baseline to probe adaptation options to climate related risks through assessing farmers' perception and local adaptation mechanisms in order to formulate mitigation strategies (Thomas et al., 2007; Stage, 2010; Belaineh et al., 2012). On the other hand, the farmer perception must be integrated with research information and proposed technologies in order to reduce the vulnerability and strengthen the adaptive capacity of communities.

The Mieso-Assebotplain in Eastern Ethiopia is one of the areas where staple food crops are extensively grown under high rainfall variability and unpredictability, strong winds, higher temperature and high evapotranspiration (Mamo, 2005). Therefore, apart from understanding meteorological variability and change on crop production and productivity *per se*, it is important to know the perception, and adaptation mechanisms of communities so as to develop viable climate change and variability adaptation options in a given area. Therefore, this study

was conducted to assess the perceptions of farmers to climate change and increased climate variability, and the likely adaptation options used in crop production. The farmers' sources of climate change information and barriers to adaptation were also investigated in this study as these perceptions determine what farmers consider as alternative best adaptation options.

## MATERIALS AND METHODS

### Study area

The study was conducted in Mieso-Assebot Plain, located in Eastern escarpment of the Central Rift Valley of Ethiopia that forms the heart and corridor of the Ethiopian Rift Valley (Figure 1). The geographical location of the area ranges between 8° 48' 12"- 9° 19' 52'N latitude, 40° 9' 30' and 40° 56' 44' E longitudes and altitude varying from 1107 to 3106 m above sea level. According to Lemma (2008) and Worku (2006), Mieso is dominated by silty clay loam soil texture with slightly alkaline pH ranging from 7.8 to 8.3. The farming system of Mieso is dominated by crop production. The major crops grown in the area include sorghum (66% of cultivable land), maize (24%), common bean and sesame as staple and cash crops (Kidane et al., 2006).

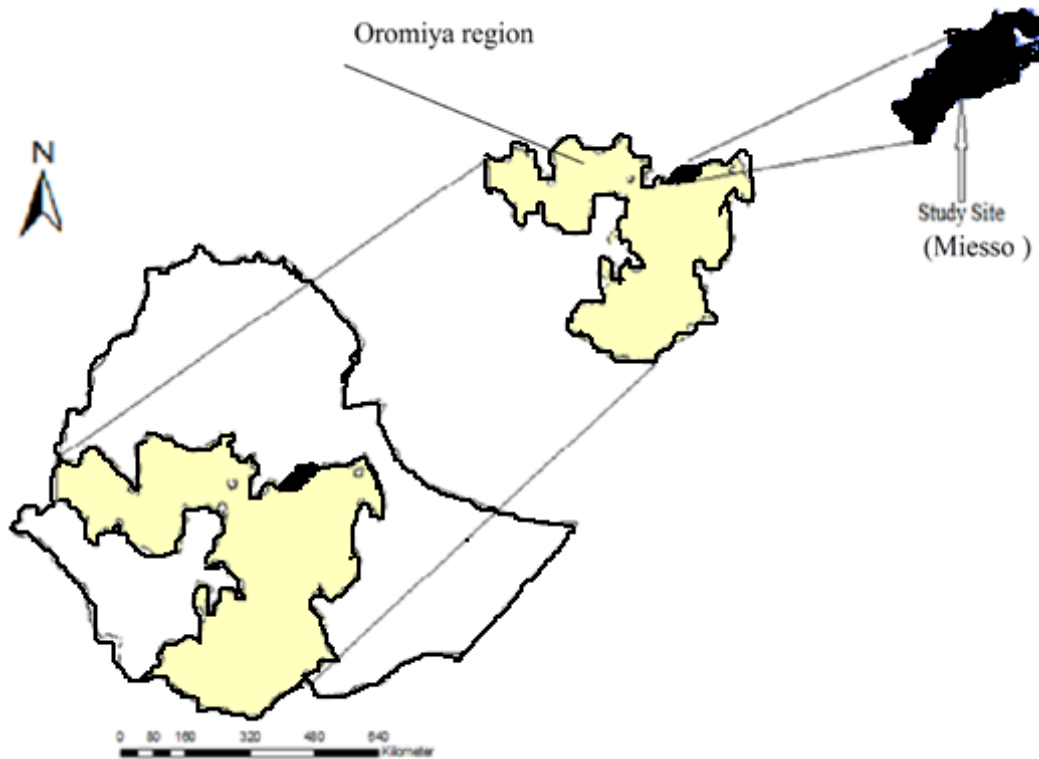
Mieso-Assebot plain is predominantly categorized under hot and warm sub-moist agro-ecological zone (MoA, 1998), receiving annual average rainfall of 727 mm distributed in a bimodal pattern. The first rainy season extends from March to May while the second (main rainy season) extends from June to September (NMSA, 1996). The annual mean minimum and maximum temperature of the district is 15 and 30.6°C, respectively.

### Data collection

Primary data were collected through structured questionnaire using farmers' participatory methodologies which include formal interviews, direct observations and oral discussions. Data were collected on farmer perceptions of magnitude of change in climate patterns along with their underlying causes and consequences as well as the adaptation strategies used in crop production to tackle the risks associated with climate variability and change. Others were perception of farmers on the climate change impacts using indicators such as diversity of livelihood strategies, changes in crop diversity, change in crop management practices, and access to and knowledge of climate related helpful information for their farm level decision that has been in use in the past fifty years. The major constraints to using existing adaptation options were assessed through the questionnaire survey. The questionnaire was pre-tested and improvement made on the results obtained from the pre-test. Long-term temperature and rainfall data of Mieso station were obtained from National Meteorological Service Agency (NMSA, 1996) which was analyzed using Microsoft Office Excel 2007 to present patterns and trends of rainfall and temperature in the form of graphs. The farmers' perceptions were then compared with the meteorological record data analysis.

### Sampling technique and data analysis

A multi-stage sampling technique was used to select five Peasant Associations (Gorbo, Husse-Mandera, Hunde-Misoma, Odabala and Torbayo) and draw sample farmers for the study. The questionnaire was administered into a total of 75 farmers of the district (15 from each Association). Household heads above the age



**Figure 1.** Geographical location of the study area.

of 50 were purposively administered the questionnaires, as more experienced and matured farmers are better at distinguishing climate variability from merely inter-annual variation of weather scenarios (Ishaya and Abeje, 2008). The total sample size was proportionally categorized into primary adopters (50) and non-adopters (25) of new technologies while growing sorghum to make their living. The crucial reason for this category is to compare the perception and adaptation mechanisms between technology adopters and non adopters. Agricultural office workers and development agents of the districts were involved in selecting the farmers.

Qualitative data collected through interview were examined and presented in different forms. Quantitative data were edited, coded and entered in a computer and Statistical Package for Social Science (SPSS) software version 17.0 spread sheet was used for the analysis (Greasley, 2008). Descriptive statistics such as mean, frequency and percentages were used for analysis of the data. Multiple response questions were analyzed so as to give frequencies and percentages. Tables, pie and bar charts were used to present different variables.

## RESULTS AND DISCUSSION

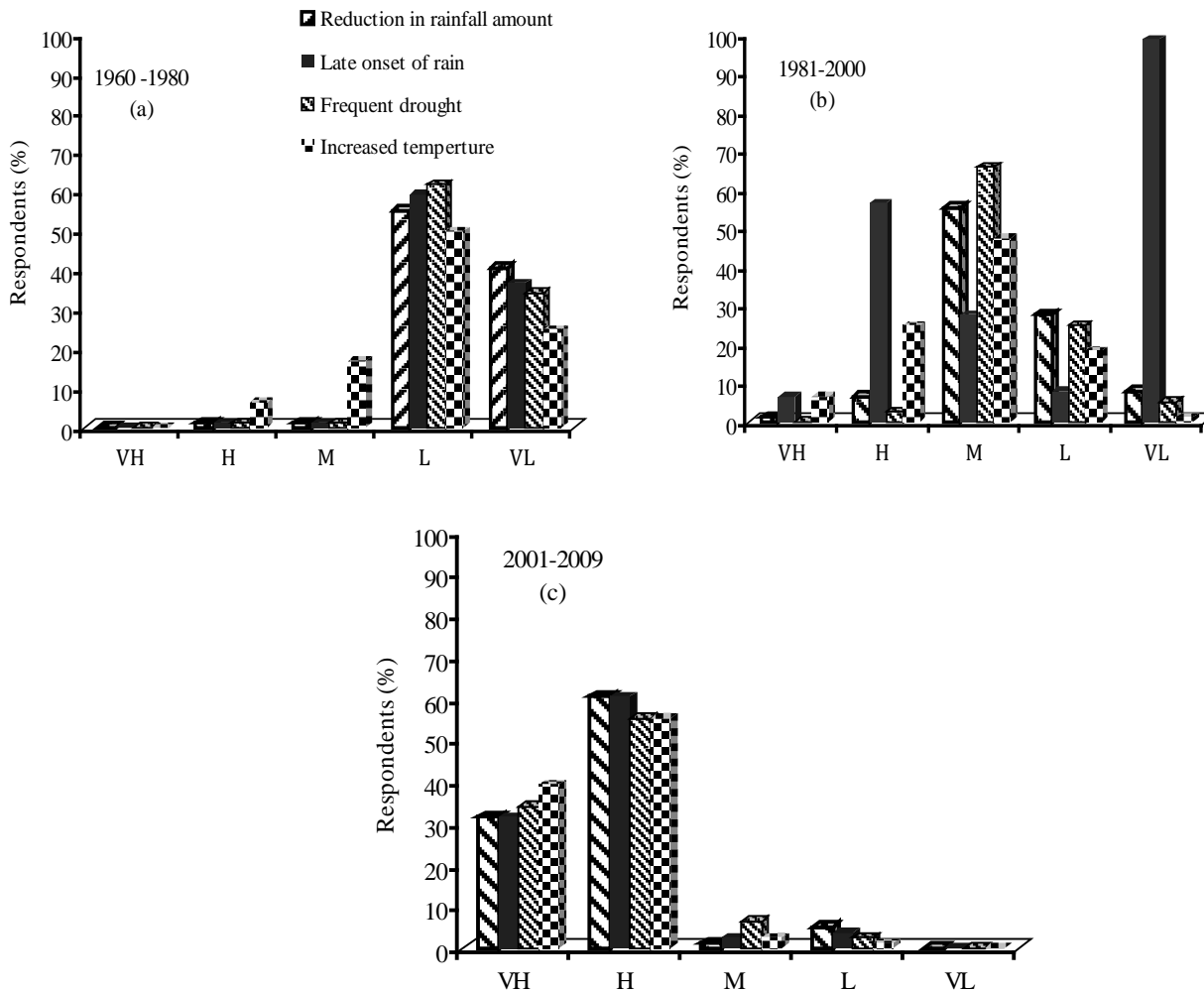
### Local perception on climate changes

Farmers' perceptions on climate variability and changes over the last fifty years (1960-2009) were assessed (Figure 2) in comparison with measured climate records (Figures 3, 4 and 5). The majority of farmers rated the reduction in rainfall amount as low during the period ranging from 1960-1980, medium during 1981-2000, and

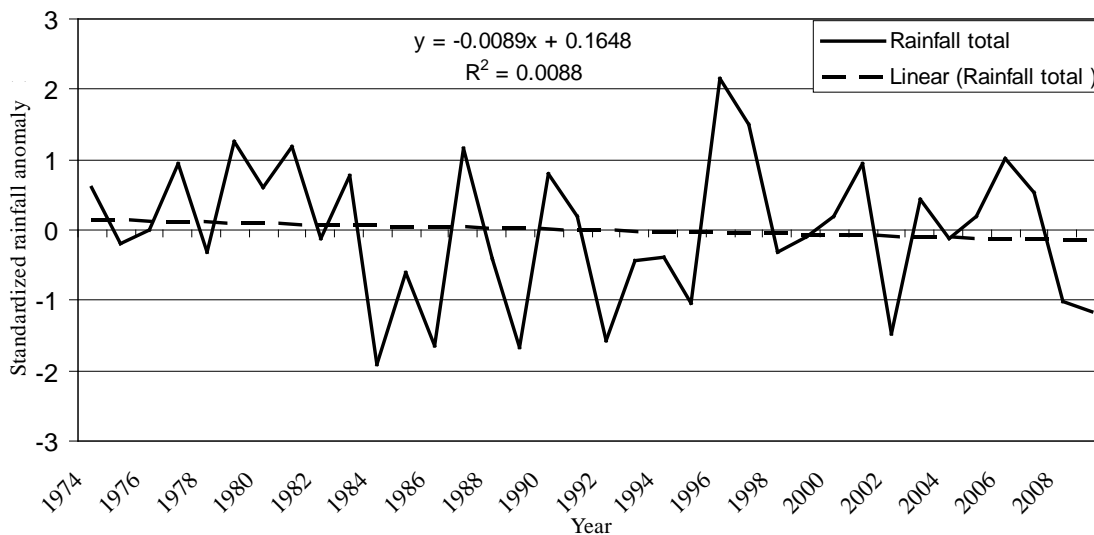
high and very high in the 2000s (Figure 1a, b and c). The farmers also opined that the rainfall amount was decreasing progressively every year since 1960s and resulted in drought conditions year after year. The great majority of farmers also indicated that changes which occurred in their ecosystems are related to severe droughts.

In view of that, the farmers ranked the frequency of droughts as low and very low, moderate, high and very high during 1960-1980, 1981-2000 and 2001-2009, respectively. However, the record data on rainfall from 1974-2009 showed that annual and seasonal (March-April-May and June-July-August-September) rainfall trend did not exhibit great reduction in amount except its variability from year to year (Figures 3 and 4). This result is in agreement with previous study on rainfall trend in Ethiopia (Sileshi and Zanke, 2004; Cheung et al., 2008). These indicate that the farmers were not able to differentiate between consistent changes in climate and yearly rainfall fluctuations.

Regarding temperature, most of the farmers interviewed perceived long-term changes in temperature. The farmers are of the view that the rise in temperature is as low (50%) and very low (25%) in the 1960s; moderate (47%) and high (25%) in the 1990s, high (55%) and very high (39%) in the 2000s (Figure 2). By and large, the analysis showed that the farmers' perception of increasing temperature is in accordance with the



**Figure 2.** Farmers' perception of extent of change in climate patterns over the last fifty years. VH = very high; H = high; M = moderate; L = low; VL = very low.



**Figure 3.** Annual rainfall trend in the study area.

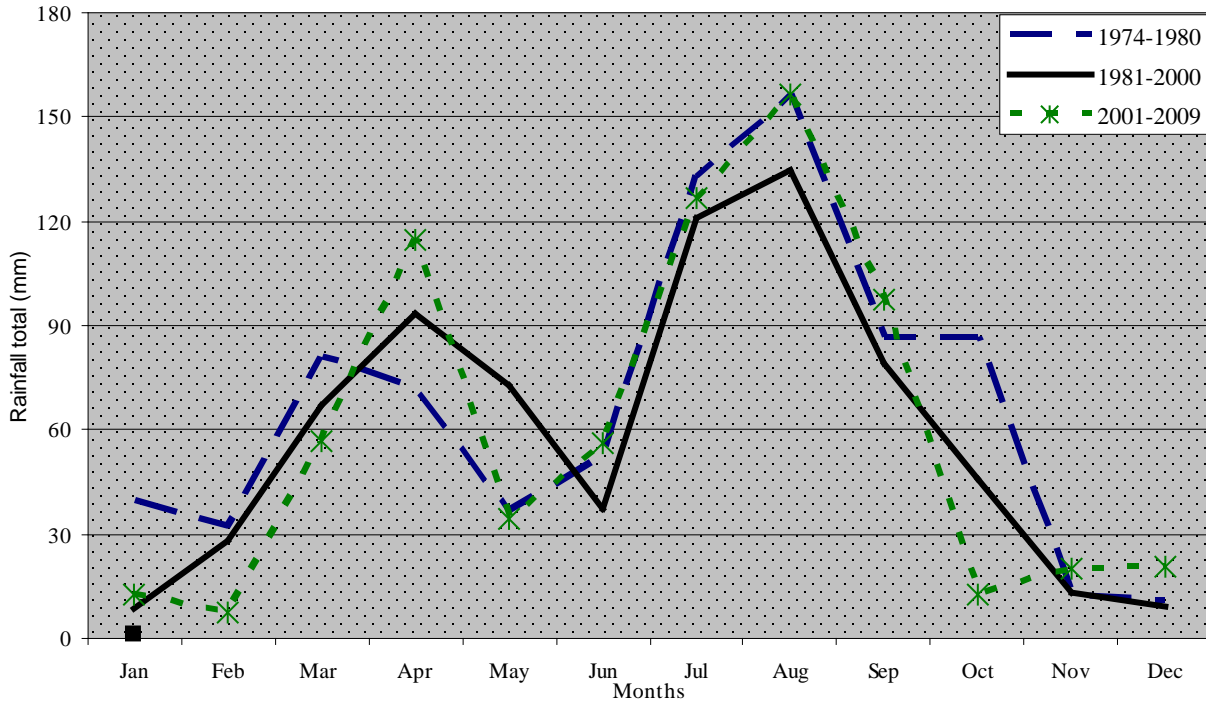


Figure 4. Monthly rainfall trend in the study area.

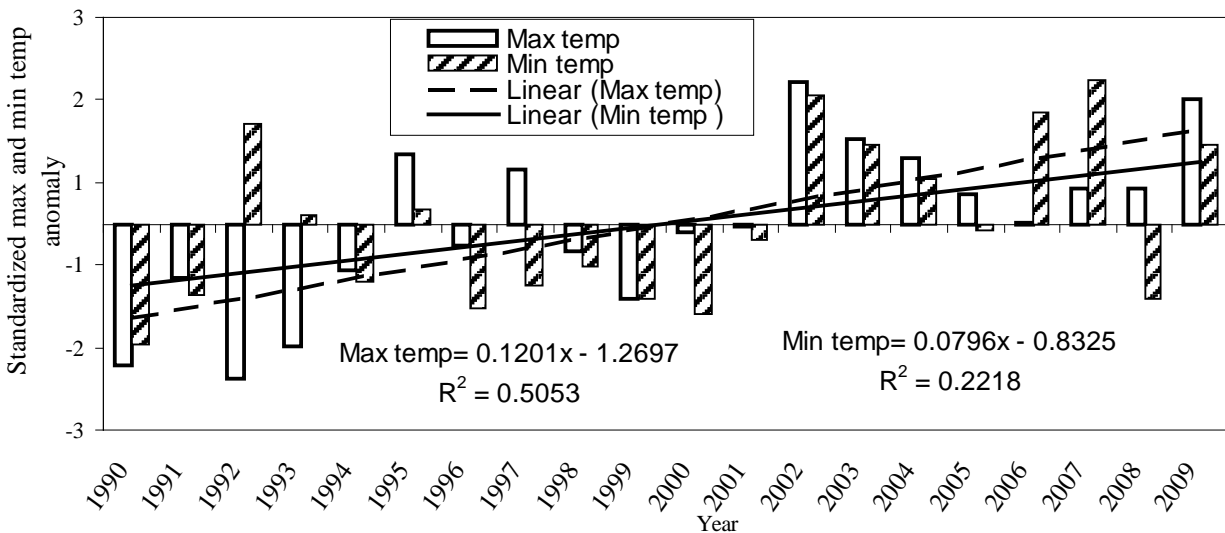


Figure 5. Annual average minimum and maximum temperature trend at Mieso.

statistical record of temperature data (Figure 5). This apart, most of the respondents perceived a shift in onset dates of rainfall, early cessation of rainfall (57%) and erratic rainfall distribution (41%). This corroborated the findings of Mengistu (2011) and Belaineh et al. (2012) which showed awareness of farmers to increased temperature, changes in timing of rains and frequent drought than it was before in central Tigray and Western

Hararghe of Ethiopia.

Generally, using their indigenous knowledge and longer years of farming experience, majority of the respondents interviewed had a clear awareness of changing climate. The majority of respondents' awareness on increasing temperature could be attributed to the fact that more experienced sorghum growing farmers were selected as respondents for this study. Similar results were reported



**Table 1.** Farmers perception of major causes of change in climate patterns.

Variable	Percent of respondents*		Total
	Technology Adopters	Non technology adopters	
Gods anger	61.2	76.9	66.7
Deforestation	69.4	53.8	64.0
Increased population pressure	10.2	23.1	14.7
Burning fossil fuel	4.1	3.8	4.0
Concentration of greenhouse gases in the atmosphere	0	0	0

\*Percentages do not add up to 100% because of multiple responses.

**Table 2.** Farmers' perception of risks (consequences) of climate variability and change.

Variable	Percent of respondents*	
	Serious problem	Very serious
Frequent total crop failures	4.0	96.0
New pattern of diseases and pests of crops	4.0	96.0
Appearance of new weed species	42.7	57.3
Shortage of feed for animals	5.3	94.7
Water scarcity or shortage	25.3	74.7
Loss of biodiversity and forest resources	9.3	90.6
Increased soil degradation (fertility and erosion)	48.0	52.0

\*Percentages do not add up to 100% because of multiple responses.

in South Africa and Nigeria in that farmers with more farming experience perceived changes in climate as compared to their less experienced counterpart (Maddison, 2006; Ishaya and Abeje, 2008; Gbetibouou and Ringler, 2009).

### Farmers' perception on causes of climate change

About 66.7% of respondents (61% technology adopters and 77% of non adopters) were convinced that the vagaries of climate were a sign of divine anger, that is, punishment from God (Table 1). For example, drought with serious consequences and diseases epidemic to crops and humans, and regular crop infestation by pests were God's punishment. Likewise, most of the respondents (64%) believed that changes in climate patterns were mainly attributed to deforestation (tree cutting and environmental destruction) by the communities, either for short-term economic gains or an attempt to expand arable land. For instance, one of the respondents (Code GR-15) detailed changes in rainfall pattern linked with forest resources as follows: 'Forests attract wind; winds hold (attract) rain; rain comes from mountains and forested areas to other places'. Hence, he concluded that deforestation is the major factor causing climate changes'. Ishaya and Abeje (2008) reported that majority

of farmers attributed climate changes to human activities such as deforestation (cutting trees for fuel, roofing and farm land extension).

On the other hand, 14.7% of respondents stated that increased human population that put mounting pressure on natural resources was a major cause of changes in climate patterns. Likewise, 4.1% of technology adopters and 3.8% of non-adopter farmers indicated that fossil fuel burning which comes from other areas or industrialized countries was the cause of climate change at and around the area. This result is in line with the study conducted by Manyatsi et al. (2010) in that a significant number of respondents did not provide any scientifically proven cause of climate change.

### Consequences of climate variability and change

Farmers in Miesso areas noted high infestation of crops by new patterns of diseases such as head smut (*Sphacelotheca sorghi*), leaf blights (*Exserohilum turcicum*) and pests such as shoot fly (*Atherigona soccata*) and frequent total crop failures due to reduced rainfall amount, changes in timing of onset of rains and high temperature (Table 2). Increased pest damage may arise from changes in production system and production of crops in warmer climatic regions where plants are

**Table 3.** Diversity of crops grown by farmers at Miesso over the last 50 years.

Period	Diversity of crops grown (number)		
	Maximum	Minimum	Mean
1960-1980	10	2	5
1981-2000	10 <sup>+++</sup>	1	4
2001-2007	5 <sup>++</sup>	1	3 <sup>+</sup>
2008- recent	4 <sup>+++</sup>	1 <sup>*</sup>	2 <sup>**</sup>

\*Sorghum (*Sorghum bicolor*); \*\*Sorghum and maize (*Zea mays*); \*\*\*Sorghum, maize, sesame (*sesam umindicum*) and soybean (*Glycine max*); + Sorghum, maize and sesame; ++Sorghum, maize, sesame, soybean and tef (*Eragrostis tef*); \*\*\*Sorghum, maize, barley (*Hordeum vulgare*), tef, sesame, lentil (*Lens culinaris*), soybean, wheat (*Triticum aestivum*), linseed (*Linum usitatissimum*) and cowpea (*Vigna unguiculata*).

more susceptible to pests (Mary and Majule, 2009). In addition, the local farmers observed various forms of crop infestations with new weed species that reduced the quality and quantity of crops produced. Moreover, many respondents mentioned shortage of feed for animal as a very serious effect of climate variability and change that caused loss and weakness of oxen (Table 2).

Furthermore, the majority of respondents perceived water shortage, great loss of biodiversity and forest resources through excessive de-forestation, and decline in soil fertility as the most important effects of climate variability and climate change. Generally, the outcome shows the sensitivity of social, economic and environment aspects of Meisso farmers (Table 2) to the impacts of climate variability and change. Hence, the interplay between the above climate variability and change consequences and its direct adverse effect on crop yields are the source of vulnerability of production system the farmers at Miesso faced.

**Changes in crop diversity (1960-2009)**

The majority of farmers revealed that they have switched over to cultivation of only two crops (sorghum and maize) out of diverse types of crops they were earlier cultivating as a result of change in climate patterns (Table 3). Due to losses in climate events that were repeated over time, capacity of crops to maintain productivity has reduced resulting in the withdrawal of crops from production systems. For the different peasant associations assessed, the farmers also recognized that different crops and some species of sorghum (land race or local varieties) are no longer being farmed due to the negative effects of climate variability and change on the productivity of the crops (Table 3).

**Changes in farming practices due to climate change**

As a result of negative impacts of change in climate

patterns, 93% of the respondents changed farming practices. Most of the farmers revealed that decreased tillage frequency, increased frequency of weeding and increased seed rate are practiced in recent periods than before (Table 4). The majority of farmers associate the decrease in tillage frequency with drought and delay in onset of rain as land becomes dry and difficult to plough and feed shortage leads to oxen weakness. Greater use of seed rate is attributed to recover damaged crops due to lack of precipitation which hinders germination of cultivated seeds. Moreover, the highest proportion of households with crop production in their farming portfolio chose not to use farm inputs (fertilizer, herbicides and pesticides). According to the respondents, this situation has resulted in a good opportunity for weeds to stay on cropping land, out compete crops and increased frequency of weeding.

The other farm practice changed include, intercropping, crop rotations and fallowing (Table 4). The increase in fallowing practice is attributed to frequent drought and power shortage. As a result of the impacts of climate change, most of the farmers showed the tendency to allocate more lands to improved sorghum varieties (drought tolerant or early maturing) than local varieties in the 2000s. These findings are in line with a study by Lema and Majule (2009) in semi-arid zone of Tanzania, who reported that farmers adopted tillage methods and other agronomic practices in the face of climate variability and changes risks in order to maximize yield.

**Source of climate information**

More than 97% of the respondents rated climate information availability from high to very high to their day to day activities. However, the majority of farmers did not have adequate information on climate variability and change for farm level decision making. The limited climate information accessible to farmers was through radio in the form of daily weather forecast (Figure 6). But, the farmers indicated that they did not trust the weather information dispatched through radio. The feeling of the farmers was that the weather information broadcast by radio was not specific to their location or region. The farmers also indicated that at times the season was forecast as good and they invested high in terms of inputs but later it turns out a dry season. The other sources of climate information used include expecting from God (32%), religious leaders and neighbors (4%), and market and radio (9%) (Figure 6).

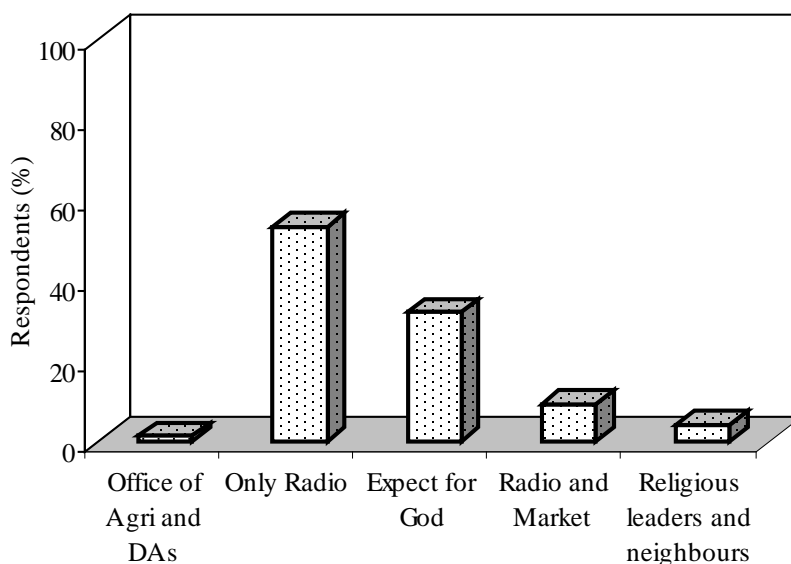
**Adaptations to climate variability and change**

Adaptation measures and practices followed by Meisso farmers to combat the adverse effects of climate variability and change over the last fifty years are mostly followed as one or in combination with another measure.

**Table 4.** Changes to farming practices at Mieso over the last 50 years\*

Cropping practice	1960-1980	1981-2000	2001-2007	2008/09
Frequency of tillage	H	H	L	L
Frequency of weeding	L	L	H	H
Fertilizer application	N	N	N	N
Mulches	H	H	H	L
Intercropping	H	H	L	L
Seed rate (kg/hectare)	L	L	H	H
Crop rotation	N	N	L	L
Fallowing	N	N	N	H
Pesticides and herbicides	N	N	N	N
Use of improved seed	N	N	H	H

H = High; L = low; N = Not practiced (used); \* = the data are based on the highest percentage of respondents.

**Figure 6.** Source of climate information to farmers in Mieso area.

Despite the fact that, livelihood adaptation strategies chosen are not free from constraints a combination of several strategies are used by farmers to cope with the impacts of climate change (Belaine et al., 2012). They are grouped as agronomic or crop management, technology adoption and promotion activities, and livelihood adaptation strategies (Table 5).

The dominant adaptation systems are using different planting dates (86.7%) and on farm soil and water conservation practices (80%). The greater shifting of planting dates was for the purpose of reducing the risks of crop damage during germination due to dry spells soon after sowing. Likewise, Komba and Muchapondwa (2012) reported that large size owned farmers preferred crop and variety diversification than planting dates to easily spread climate change risks. The use of on farm soil and

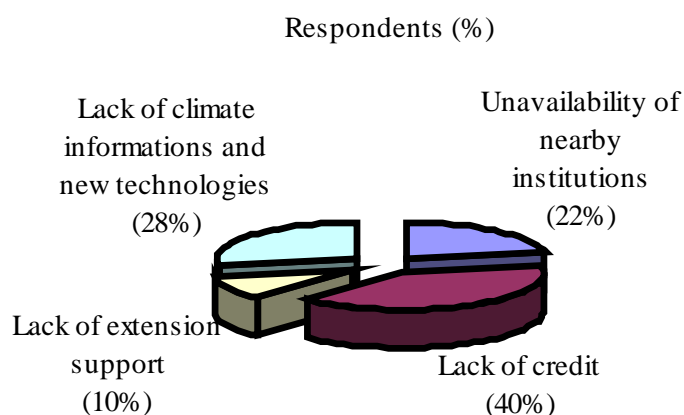
water conservation practices as an adaptation method is associated with the efficient use of scarce rainfall received over the area. Other adaptation strategies practiced by farmers include application of fertilizers and chemicals (4%) and water harvesting techniques for supplemental irrigation (34.7%). The low use of fertilizers, chemicals and water harvesting techniques as on farm adaptation mechanism could be due to the fact that these practices require high capital investment. The results of farmers agronomic adaptation strategies practiced by Mieso farmers are similar to autonomous adaptation strategies reported by FAO (2007) and Hassan and Nhemachena (2008), which were carried out in response to or in anticipation to changing climate patterns.

Since crop cultivation is the dominant livelihood strategy of farmers, growing of local/land race cultivars

**Table 5.** Types of climate variability and change adaptation strategies used by farmers in Meisso.

	Adopter (%)*	Non-adopter (%)	Total (%)
<b>A. Agronomic or crop management</b>			
Use of different planting dates	89.8	80.8	86.7
Use of fertilizers and chemical	6.1	-	4.0
Use of on farm soil and water conservation practices	81.6	76.9	80
Use of water harvesting techniques for supplemental irrigation	38.8	26.9	34.7
<b>B. Technology adoption</b>			
Use of local/land race varieties	81.6	92.3	85.3
Use of drought resistant varieties	59.2	19.2	45.3
Use of early maturing varieties	73.5	26.9	57.3
<b>C. Livelihood adaptation options</b>			
Changing from farming to non-farming	10.2	38.5	20.0
Move to different site	10.2	7.7	9.3
Use of credit	18.4	7.7	14.7

\*Percentages do not add up to 100% due to multiple responses.



**Figure 7.** Constraints that hinder climate variability and change adaptation of farmers in Miesso area.

(85.3%) is one of the adaptation option for climate variability and change. Greater use of local varieties is associated with their use as animal feed resources during severe droughts because of their good fodder quality and productivity. The use of drought resistant varieties (45.3%) and early maturing crop varieties (57.3%) are other adaptation strategies practiced by farmers. Planting short season and drought resistant crop varieties increases the chances of successful harvests despite adverse climatic conditions (Mano and Nhemachena, 2006). These adaptation mechanisms are in line with the adaptation practices reported by Cox et al. (2008). Livelihood diversification (shift from farming to non-farming such as charcoal making, firewood sale) was one of the most commonly used adaptation methods by the

farmers (Table 5), whereas temporary migration (9.3%) to other places was the rarely practiced adaptation method during severe conditions. Likewise, 14.7% of respondents used credit (from government or local lenders) as an adaptation strategy against the shocks of changing climate patterns to recover and develop resilience for the next event (s). Similar adaptation strategies were reported from various studies conducted in Ethiopia, Zimbabwe, South Africa and Nigeria (Mano and Nhemachena, 2006; Hassan and Nhemachena, 2008; Deressa et al., 2009; Mengistu, 2011; Belaineh et al., 2012). The proportion of technology adopter farmers that use the adaptation mechanisms is almost equal to the proportion of non-adopter farmers except the high proportion of technology adopters in using early and drought resistant crop varieties.

**Major constraints to adaptation**

The survey results indicate that, there are four major constraints to climate variability and change adaptation by sorghum farmers in Miesso area. These are unavailability of nearby supporting organizations (that provide technologies, farm inputs, information related to farm activities and climate), lack of credit, lack of support from extension workers and lack of climate information and new technologies (Figure 7).

Lack of credit for input purchase (improved seed, fertilizer, chemicals) is the prominent constraint to adapting climate variability and change effects. This result is in line with the survey carried out across Africa by Maddison (2006), where 33% of respondents in Ethiopia reported lack of credit as the main constraint to

adapting to climate change. Lack of information on climate and new technologies is the second main barrier to adaptation in Mieso. This is also related to weak support from extension and research in the provision of up-to-date information and technologies.

### Summary and recommendation

The analysis of perception of farmers on climate variability and change indicated that the majority of farmers were aware of a decline in rainfall amount, increasing temperature, shift in onset dates of rainfall, early withdrawal of rains and frequent drought occurrence. As a result, majority of farmers indicated decreasing diversity of cultivated crops, changes in farming practices and reduction in crop yields due to changes in climate patterns in their area. Production of drought or heat tolerant crop cultivars with optimum maturity periods are recommended to offset the adverse effects of increasing temperature. Moreover, introduction of new crops, varieties and crop management practices that goes in line with the changing climate patterns should be the prior agenda for research and development planners in order to arrest declining diversity of crop grown in the area due to climate change. Additional advantage can be achieved by the distribution of pamphlets containing weather and climate information prepared by Ethiopian weather service. The farmers should be encouraged to stabilize their family size.

### Conflict of Interests

The author(s) have not declared any conflict of interests.

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## Full Length Research Paper

## Wood-cement composites using suitable mix of sawdust and fibres from veins of palm tree leaves

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Some tropical wood species are currently used in wood work and generating an important quantity of wood waste in Benin, Western Africa. Recycling these wastes through building material is a way to solve environmental challenges, but the wood resources are not inexhaustible and vegetable fibers such as *Eleais guineensis* fibers, obtained from veins of palm tree leaves are available in nature. The main concern of this study is to determine the most suitable mixes of *E. guineensis* fibers and five West African hardwood species namely *Diospyros mespiliformis*, *Khaya grandifoliola*, *Tectona grandis*, *Pterocarpus erinaceus* and *Isobertina doka* for wood-cement composites. The compatibility with cement of mixes of fibers and sawdust is studied based on measurements of cement heat hydration and compatibility indices. The tensile and compressive strengths of the composites were determined to evaluate the potential of the mixes. The results show that the woody residues inhibit the hydration reactions of cement and greatly more when containing *E. guineensis* fibers. Hydration tests indicated that all the mixes could be rated as having moderate to good compatibility with cement after hot water treatment. Mechanical tests showed that the mixes containing *Isobertina doka*, *Tectona grandis* and *Khaya grandifoliola* sawdust provided the highest mechanical strengths.

**Key words:** Vegetable fibers, sawdust, compatibility, wood-cement composites, mechanical strengths.

### INTRODUCTION

In Benin, a West African country, the forest cover is about 68% of the total superficies of 114 763 km<sup>2</sup>, according to a recent World Bank report (2010). The per capita income according to the same report is 690 USD. Overall wealth of this country has an important component that is derived from forest resources. Many tropical species are

identified to be hard wood and generate significant volumes of wood commercially viable. Consequently, large quantity of wood waste is generated in this region and will constitute a considerable environmental problem. In most of the West African countries, a very moderate fraction of wood waste is used to provide energy for

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domestic use while a great proportion of such waste is consumed in the nature releasing carbon dioxide and other gas in the environment.

The re-use of wood waste as building materials is one of the few ways of tackling the problem. But the wood resources are not inexhaustible and it would be suitable to use the mixes of sawdust and vegetable fibers such as those from palm oil veins, available in the nature for wood - cement composites. Ordinary wood-cement composites obtained by mixing sawdust, water and cement have been widely investigated (Dinwoodie and Paxton, 1984; Hachmi and Sesbou, 1990; Hofstrand et al., 1984). The dimensional variations have been studied by Mougel (1992). The major well known problem occurring with regards to this topic is the aptitude of wood species to be used as wood - cement composites. Such a problem is widely discussed recently (Pereira et al., 2003, 2004). Many studies have been undertaken to assess the compatibility of wood with cement (Hachmi and Moslemi, 1989; Hachmi et al., 1990; Sandermann and Kolher, 1964).

To build houses with walls made from wood cement-composite is a way not only to solve environmental problem but to provide many other advantages. It is a very lightweight material which allows saving of money as reported in the thesis of Doko (2013). It is also a material which provides heat insulation.

Today, although a large number of wood species have been investigated such as pin wood (Semple and Evans 2000), Western Australian *malle Eucalyptus* (Semple et al., 2002), *Acacia mangium* and *Eucalyptus pellita* (Semple et al. 1999), *Amblygonocarpus andongensis*, *Brachystegia speciformis*, *Pterocarpus angolensis*, *Kaya nyasica*, *Erythrophleum suaveoleuns*, *Albizia adianthifolia*, *Sterculia appendiculata*, *Millettia stuhlmannii*, *Julbernadia globiflora* and *Afzelia quanzenzis* (Alberto et al. 2000), few information related to the compatibility of wood species with cement is available. That is the same thing with the mixes containing various tropical fibers. Moreover, it was widely discussed (Alberto et al., 2000) that the nature of wood species considerably influences the hardening of the cement depending on the origin of the tree. Evaluating some physical properties for oil palm stem as alternative biomass resources, Balkis et al. (2012) concluded that the middle and center sections of oil palm stem contained the highest amount of extractives using hot water extraction. The lowest amount of extractives was located at the bottom outer section of the oil palm stem.

Although today, researchers reveal more and more new environmental problems generated by manufacturing wood cement composite; we must keep in mind that the transformation process of the wood residues should avoid the creation of other environmental problems. Indeed, Silva et al. (2013) reported that in Brazil, the wood panel industry is one of the most important forest-based industries. Assessing the life cycle of medium den-

density particleboard (MDP), they found that unlike other regions, Brazilian MDP is produced from dedicated eucalyptus plantations and heavy fuel oil is an important energy source in MDP manufacture with a negative impact on the environment. They suggest the possibility of using alternative production MDP scenarios as substituting heavy fuel oil (HFO) for in-mill wood residues or diesel or finding other sources of wood for MDP production.

The aim of this research initiated in Benin was to determine the most suitable mixes of *Eleais guineensis* fibers and five West African hardwood species for wood-cement composites. The first step in assessing the suitability of different mixes containing wood species and vegetable fibers for cement composites involves testing whether the mix significantly inhibits the hydration reaction of Portland cement. Compatibility with cement of mixes of *E. guineensis* fibers and five wood species based on the measurement of cement hydration temperature and compatibility indices was studied. In the second step, mechanical tests were carried out on moulded blocks to confirm hydration tests as indicated by Andy and Land Zhongli (1986). In the third step, the suitability of mixes for wood-cement composites were evaluated by carrying out tensile and compressive tests on the samples made from mixes of vegetable fibers and sawdust.

## MATERIALS AND METHODS

Sawdust taken from sawmills for five wood species available in Benin (Figure 1a) were used in this study: *Diospyros mespiliformis*, *Khaya grandifoliola*, *Tectona grandis*, *Pterocarpus erinaceus* and *Isobertina doka*. *Eleais guineensis* fibers (Figure 1b) are vegetable fibers obtained from ground oil palm veins previously dried.

In order to assess the influence on the compatibility indices of the treatment method applied, the mixes (*E. guineensis* fibers and wood sawdust) were pre-treated firstly with cold water and secondly with hot water. Treatment in cold water consisted of drenching during 48 h and washing thoroughly sawdust and fibers in water at ambient temperature. Treatment in hot water consisted of drenching for 48 h and washing sawdust and fibers in water at 80°C because of their great degree of inhibition assumed (Badejo, 1989; Hachmi and Moslemi, 1989; Pereira et al., 2003).

After washing, both the sawdust and *E. guineensis* fibers were dried in a kiln at 105°C within 48 h then separated by sieving in three size classes. Class retained for the tests was 0, 1 - 4 mm. The type of cement used was CPJ-CEMII 35 manufactured in SCB Lafarge Company and locally available in Benin.

### Measurement of cement hydration temperature and compatibility indices

The mass ratios used were: Sawdust/*E. guineensis* fibers/cement/water mass ratio of 12:3:200:90.5 g inspired from the work of Weatherwax and Tarkow (1964) in which wood/cement/water mass ratio was 15:200:90.5 g. In this study, the wood is considered as the mix of sawdust (12 g) and *E. guineensis* fibers (3 g). The lower proportion of vegetable fibers in wood (1:5) has been adopted because of its probable great degree of inhibition presumed.





Figure 1. Sawdust (a) and fibres from veins of palm oil leaves (b).

Table 1. Most convenient ratios for wood species.

Wood species in the mixes of sawdust and <i>Eleais guineensis</i> fibers	Water/cement/ ratio in weight
<i>Diospyros mespilliformis</i>	00.85
<i>Khaya grandifoliola</i>	0.87
<i>Tectona grandis</i>	0.61
<i>Pterocarpus erinaceus</i>	0.84
<i>Isobertina doka</i>	1.09

Cement control sample: 200 g of cement mixed with 80 ml of water was used (Weatherwax and Tarkow, 1964).

The samples were thoroughly mixed with water in a sealable polyethylene bag for 2 min. Immediately after mixing, the tip of a temperature thermocouple (type K) was taped to the outside of sample bag and enclosed within the body of the wood-cement mix by folding the bag and contents around it and securing the folded bag with adhesive tape. The bag was then placed in a polystyrene cup and sealed inside a flask. This process was carried out for three samples per test. All experiments were undertaken in a controlled temperature room maintained at  $20 \pm 1^\circ\text{C}$ . A cement hydration temperature logging apparatus was used to measure the heat of hydration of the three wood-cement samples for 24 h. Temperatures were recorded at 5 min intervals and the curves were smoothed by plotting the progressive averages of every three successive readings. Maximum heat of hydration temperature ( $T_{\max}$ ) and time ( $t$ ) to reach  $T_{\max}$  were recorded and two wood-cement compatibility indices,  $C_A$  - factor and hydration rate ( $R$ ) were calculated:

$$R = (T_{\max} - T_{\min})/t.$$

$T_{\min}$ : Temperature attained during the time when not more than three repeated values are recorded.

$$C_A = \frac{A_1}{A_2} * 100$$

Where,  $A_1$ : Area under the wood-cement sample hydration curve,

$A_2$ : Area under the control sample curve.

Control sample is made with cement only. Then, wood species

were classified as compatible, moderately compatible or incompatible with cement based on the extent to which they delayed cement hydration (Hachmi et al., 1990).

#### Mechanical tests on moulded blocks

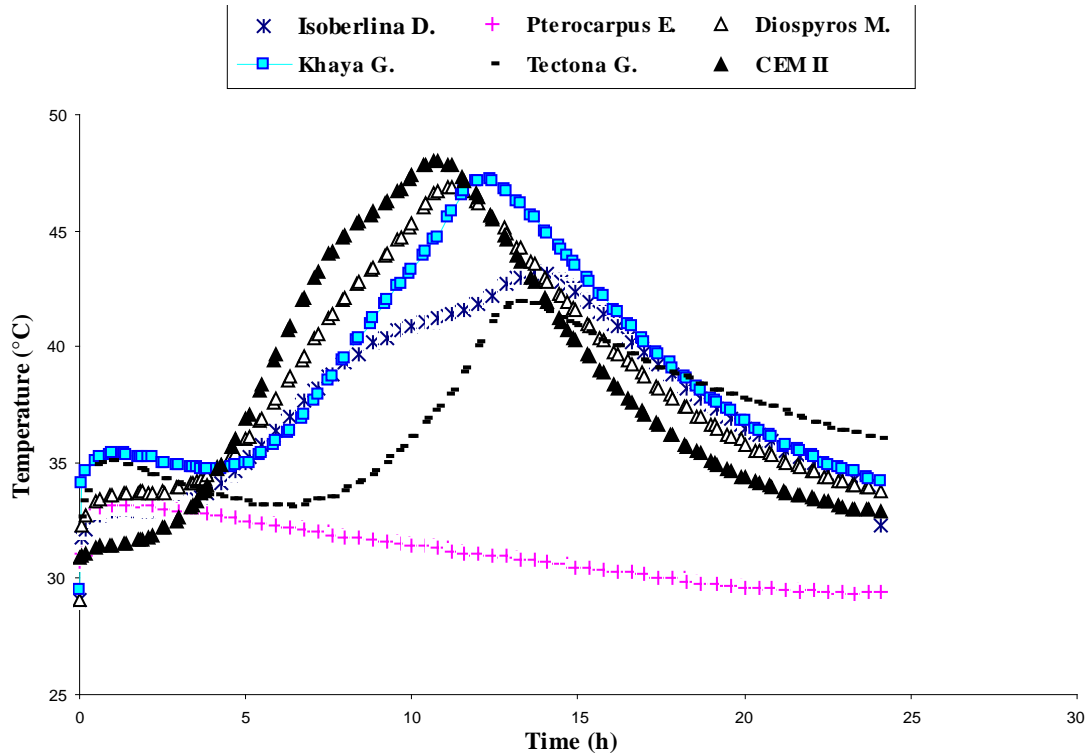
The evaluation of the aptitude of mixes to wood work by measuring cement hydration temperature and compatibility indices has been completed by mechanical tests on moulded blocks. Thus, sawdust and fibers treated in hot water, cement and water were mixed respecting the following ratio: sawdust/fibers/cement/water mass ratio of 60/15/1000 /452.5 g according to the ratio adopted in the work of Andy and Land Zhongli (1986) in which total mass of wood was 75 g.

For each batch of mix, twelve cubic specimens (50 x 50 x 50 mm) were used to conduct compressive tests after 28 days of curing in water in room at 20-25°C.

#### Mechanical tests on wood-cement composites

The sawdust, vegetable fibers, cement and water were mixed according to the most convenient ratio for wood species. For all species, the wood/cement ratio in weight was about 0.80 as found in the work of Tchouhali (2002), but the water/cement ratio in weight varied as indicated in Table 1 with consistency test in fresh mixtures.

The mixes was placed in steel mould and compacted. For each batch of mixture, twelve cubic specimens (50 x 50 x 50 mm) and twelve cylindrical specimens with diameter: 50 mm and height: 100 mm were used to conduct compressive and indirect tensile (split tensile) tests, respectively. After 24 h, the boards were de-clamped and conditioned for 28 days at 20°C and 65% relative humidity



**Figure 2.** Hydration exotherms (temperature vs. time) for neat cement1 and cement containing tropical wood treated with cold water.

**Table 2.** Compatibility indices of tropical wood species treated with cold water.

Mix	T <sub>max</sub> (°C)	T <sub>min</sub> (°C)	Time (H)	Rate (°C/H)	C <sub>A</sub> factor (%)
CEM II	47.8	31.5	8.5	1.80	100
CEMII + <i>Diospyros mespiliformis</i> sawdust + <i>Eleais guineensis</i> fibers	45.9	34	7.95	1.58	63
CEM II + <i>Isoberlina doka</i> sawdust + <i>Eleais guineensis</i> fibers	42.8	33.1	10.31	1.0	60
CEM II + <i>Khaya grandifoliola</i> sawdust+ <i>Eleais guineensis</i> fibers	46.3	34.1	7.09	1.72	54
CEM II + <i>Tectona grandis</i> sawdust+ <i>Eleais guineensis</i> fibers	41.2	33.0	5.29	1.54	47
CEM II + <i>Pterocarpus erinaceus</i> sawdust+ <i>Eleais guineensis</i> fibers	0.0	0.0	0.0	0.0	0.0

(RH) to allow the cement to cure and gain strength.

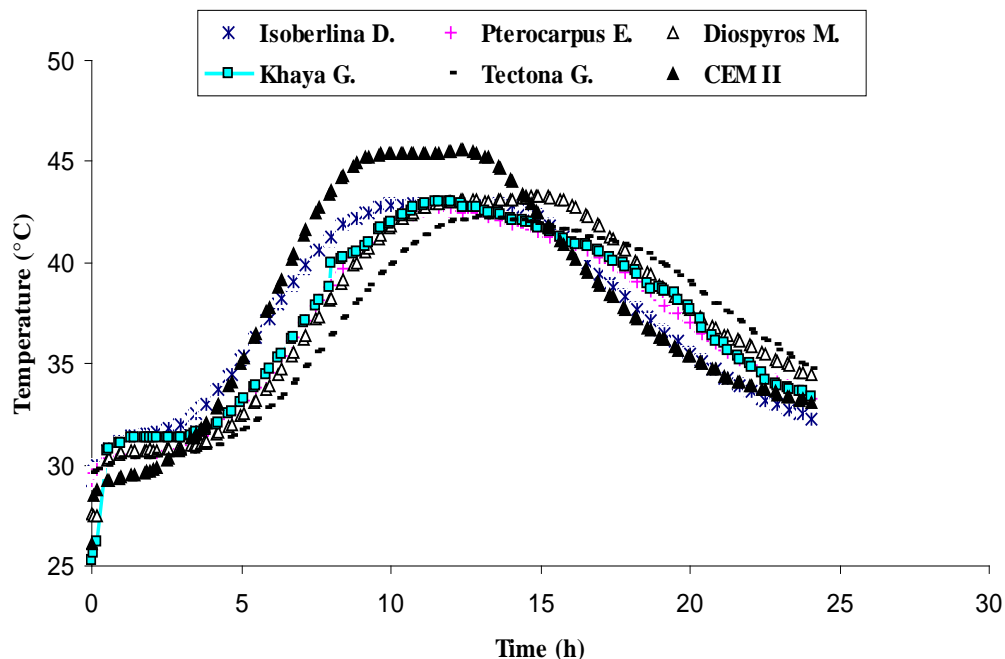
Tensile and compressive tests were carried out directly on half of the samples while others were tested after they were soaked in water at laboratory room temperature (20°C) for 24 h. After soaking, the samples were drained on paper towels for 20 min to remove excess water. Tensile and compressive tests constitute simple and relevant mechanical tests on wood cement - composites to quickly evaluate the aptitude of wood specie for wood work.

## RESULTS AND DISCUSSION

Compatibility of wood species with cement based on measurements of cement hydration temperature and compatibility indices.

From Figure 2, when the mixes of sawdust and *E. guineensis* fibers were treated with cold water, the curves indicate that in the mixture of *Isoberlina doka* and *Diospyros melsiformis* species, hydration reactions started very earlier (about 3 hours after adding water) than in other mixtures. In the mixtures of *Tectona grandis* and *Khaya grandifoliola* species, hydration reactions started about 7 and 5 h, respectively. The curve corresponding to *Tectona grandis* species presented a great and favourable tendency in developing heat hydration even over 30 h.

From Table 2, *Isoberlina doka* and *Diospyros melsiformis* species have yielded the highest compatibility indices with C<sub>A</sub> - factor equals to 60 and 63%



**Figure 3.** Hydration exotherms (temperature vs. time) for neat cement and cement containing tropical wood and fibres treated with hot water

**Table 3.** Compatibility indices of tropical wood species treated with hot water.

Mix	T <sub>max</sub> (°C)	T <sub>min</sub> (°C)	Time (H)	Rate (°C/H)	C <sub>A</sub> factor (%)
CEM II	45.4	31.3	8.5	1.56	100
CEM II + <i>Isoberlina doka</i> sawdust + <i>Eleais guineensis</i> fibers	42.9	32.1	6.92	1.56	80
CEM II + <i>Khaya grandifoliola</i> sawdust + <i>Eleais guineensis</i> fibers	41.4	31.8	6.75	1.42	72
CEM II + <i>Pterocarpus erinaceus</i> sawdust + <i>Eleais guineensis</i> fibers	42.7	31.5	7.26	1.54	70
CEM II + <i>Tectona grandis</i> sawdust + <i>Eleais guineensis</i> fibers	42.3	31.3	8.17	1.55	73
CEMII + <i>Diospyros mespiliformis</i> sawdust + <i>Eleais guineensis</i> fibers	41.4	31.8	6.67	1.51	66

respectively. *K. grandifoliola* and *T. grandis* species had C<sub>A</sub>- factors equal to 54 and 47%, respectively. There is no data in the columns corresponding to *Pterocarpus erinaceus* species because of its great inhibitory effect on the cement hydration.

From Figure 3, in the case of hot water treatment, the curves of the mixtures of *I. doka* and *K. grandifoliola* species show earliest hydration reactions starting from about 2.20 and 3.75 h, respectively after mixing with water. The mixtures of *T. grandis*, *P. erinaceus* and *D. melsiformis* species started their hydration reactions about 4.10, 5.20 and 6.10 h, respectively after mixing with water. In spite of a long delay in starting hydration reactions, *T. grandis* specie had good compatibility indices as indicated in Table 3. *Isoberlina doka*, *Tectona grandis*, *Khaya grandifoliola* and *P. erinaceus* species had average C<sub>A</sub> - factors equal to 80, 73, 72 and 70%,

respectively. The lowest compatibility indices were provided by *Diospyros mespiliformis* (C<sub>A</sub> - factor equals to 66%). In general, the results indicate that the treatment of sawdust and fibers in hot water enhance notably the compatibility indices of all species as found in previous work of Alberto et al. (2000).

With simple treatment in cold water, *Isoberlina doka*, *Diospyros melsiformis* and *K. grandifoliola* species had good compatibility indices while compatibility indices of *T. grandis* and *P. erinaceus* species were negatively affected. Alberto et al. (2000) had a similar report on *Khaya* specie which indicated that *P. angolensis* and *K. nyasica* species were compatible with cement after simple treatment in cold or hot water. The contrast of the findings about *P. angolensis* species could be due to the presumed change of the nature of soil where the species has been grown.

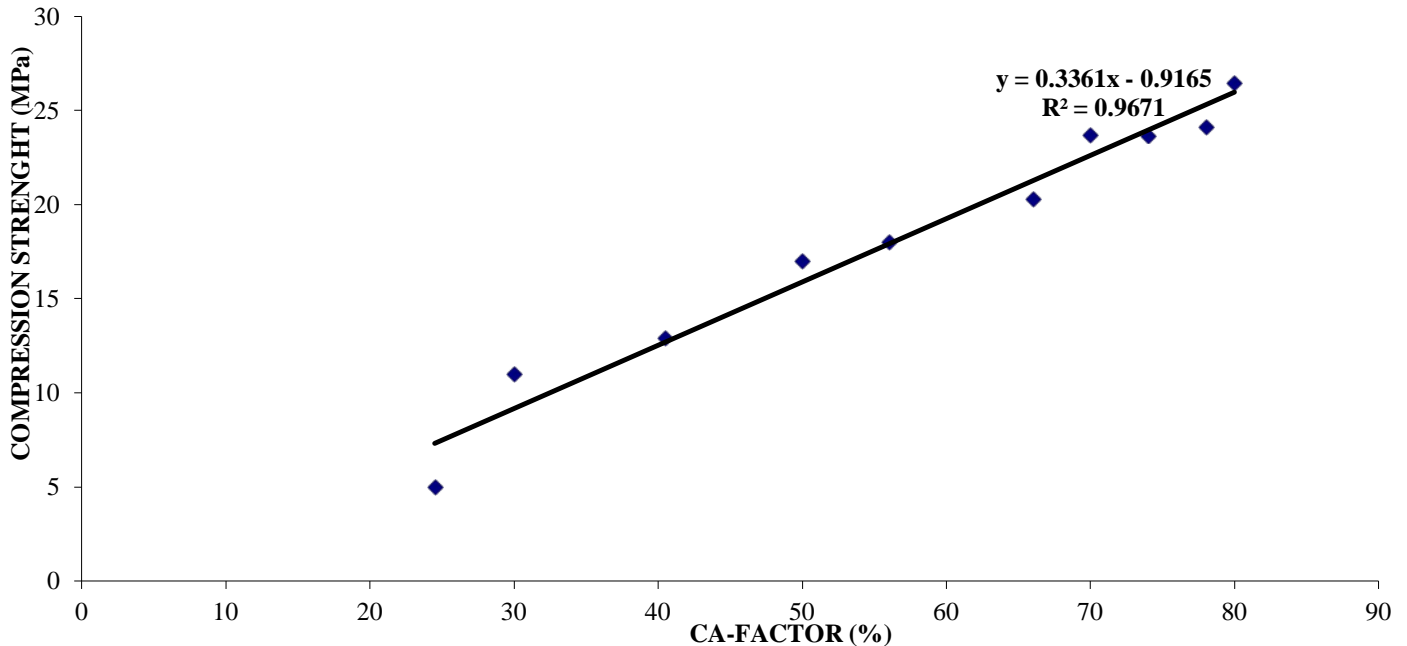


Figure 4. Evolution of compressive strengths of moulded blocks with  $C_A$ -factor.

### Characteristics of moulded blocks

The blocks have presented an average density of about  $1395 \text{ kg/m}^3$ . They could not be classified as lightweight concretes which densities vary from  $450$  to  $1200 \text{ kg/m}^3$  (Mougél, 1992). The very slight variation of the densities (minimum value  $1310 \text{ kg/m}^3$  corresponding to *Pterocarpus eurinaceus* species and maximum value  $1370 \text{ kg/m}^3$  corresponding to *Isobertina doka* species tallies with the slight variation of the characteristics of the blocks as shown in Figure 4 whereby compressive strengths vary from  $21.5 \text{ MPa}$  for *P. eurinaceus* species to  $24.0 \text{ MPa}$  for *I. doka* specie. Moreover, from Figure 4, compressive strengths values were linearly proportional to  $C_A$ - factors and such results lead to the conclusion that physical tests could be a real indicator of wood-cement compatibility (Andy and Land Zhongli, 1986). The great proportion of cement in the blocks and the relative high densities obtained constitute a major inconvenience when such material is used as lightweight material with low cost. The compressive tests were carried out on the blocks only to establish the correlation between strengths and  $C_A$  - factors.

### Mechanical strengths of wood -cement composites

In the case of cold water treatment, the highest mechanical strengths of wood-cement composite were obtained with *I. doka* and *D. mespiliformis* species both in dry and wet conditions as shown in Figure 5. *P. eurinaceus* species provided the lowest mechanical

strengths.

In the case of hot water treatment (Figure 6), *I. doka* and *T. grandis* species showed the highest strengths. Samples made from *T. grandis*, *P. eurinaceus* and *K. grandifoliola* species presented good strengths both in dry and wet conditions. *D. mespiliformis* species provided the lowest mechanical strengths. The tensile and compressive strengths of wood-cement composites were very low and decreased drastically in wet conditions (about 40%) especially with *I. doka* and *D. mespiliformis* species.

The term compatibility refers to the degree of cement setting after mixing water, wood and fibers. The performance of specific wood species depends on the chemical composition of their extractives which could be extracted with simple cold water or hot water treatment. Several works (Hachimi et al., 1990; Alberto et al., 2000; Balkis et al., 2012; Weatherwax et al., 1964) indicate that before elaborate wood-cement composite, sawdust should be treated in cold or hot water but treatment in hot water is more efficient than treatment in cold water because hot water act more deeply on the extractives. Thus, some wood species may require a more severe treatment, in NaOH 1% solution for example, in order to overcome their incompatibility with cement. The very low strengths presented in Figures 5 and 6 especially in cases of *P. eurinaceus* and *D. mespiliformis* species indicate that more severe treatment should be applied before their utilization as building material in construction. Several other techniques exist to be explored in the next investigations to enhance the mechanical characteristics

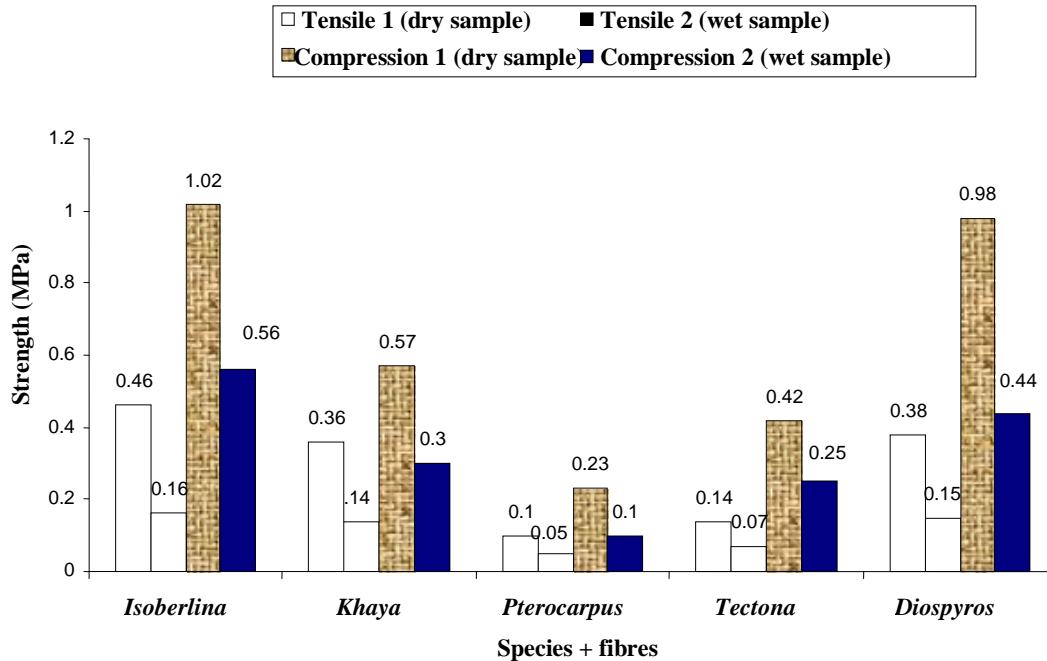


Figure 5. Tensile and compressive strengths of wood cement composites (treatment in cold water).

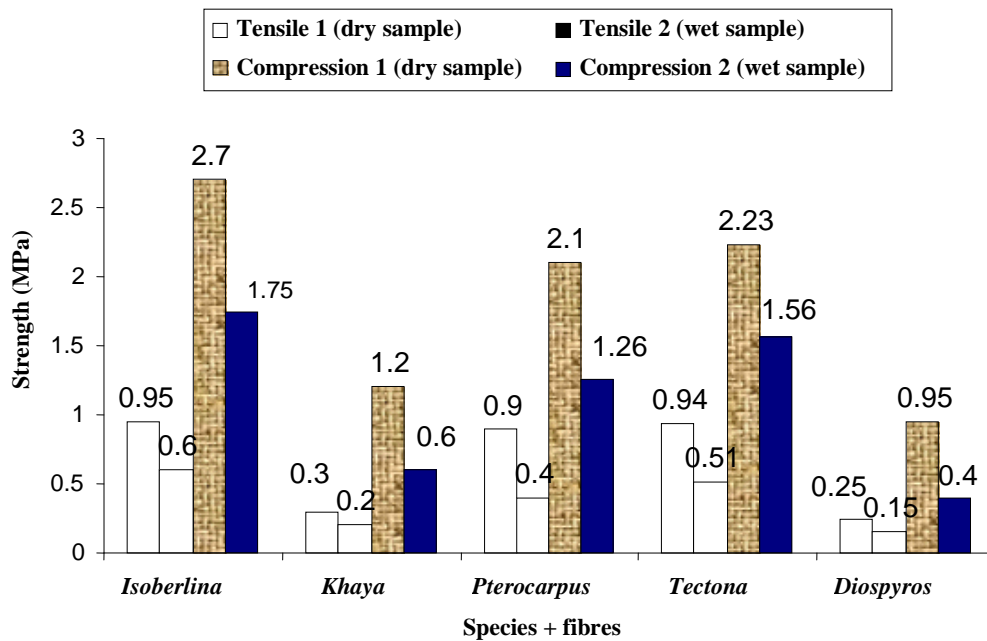


Figure 6. Tensile and compressive strengths of wood-cement composites (treatment in hot water).

of the wood-cement composite made from sawdust and vegetable fibers available in Benin. The new material can be used to manufacture lightweight bricks for walls.

**Conclusion**

In this study, the sawdust from five West African wood

species partially replaced by *E. guineensis* fibers were tested to make wood-cement composites. The compatibility study indicated that all the sawdust and fibers mixes have good aptitude to wood-cement composites. After hot water treatment which enhanced the compatibility of the most mixes, only *Diospyros mespiliformis* species became moderately compatible with cement while

the other species namely *Isoberlina doka*, *T.grandis*, *K. grandifoliola* and *P. erinaceus* species had good compatibility with cement. *T. grandis* and *P. erinaceus* sawdust containing *E. guineensis* species were greatly affected by cold water treatment.

The study confirms that physical and mechanical tests on wood-cement composites could provide quick and satisfactory results to assess the aptitude of tropical hardwood species for wood work. On the basis of the density and compressive strengths of wood-cement composite, the main factor of compatibility of the wood specie with cement could be approximately and quickly evaluated.

In wet conditions, the mechanical strengths of wood-cement composites decrease drastically (about 40%), especially *I. doka* and *D. mespiliformis* species. Such important result must be taken into account when using the composites in a humid environment. Finally, one can suggest the most suitable mixes of fibers and the five West African hardwood species for wood-cement composite in the following order: *I. doka*, *T. grandis*, *K. grandifoliola*, *P. erinaceus* and *D. mespiliformis* species. Tests will continue to be done in order to find the best way to keep very low the inhibitory effect of the wood species and the fibers on the cement hydration.

## Conflict of Interests

The author(s) have not declared any conflict of interests.

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## Full Length Research Paper

# Studies on the effect of simulated acid rain of different pH on the growth response of TMS 419 cultivar of *Manihot esculenta* (Crantz)

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The growth response of TMS 419 cultivar of cassava *Manihot esculenta* Crantz exposed to simulated acid rain of different pH was studied. The plant was exposed to simulated acid rain of pH 2.0, 3.0, 4.0, 5.0, 6.0 and 7.0 (control), respectively. Simulated acid rain induced morphological changes including chlorosis, senescence, necrosis, leaf abscission, leaf folding and death. Plant height, leaf area, fresh weight, dry weight, relative growth rate, the chlorophyll content of the leaf and the harvest index was highest at pH 7.0 (control) and significantly ( $p < 0.05$ ) decreased with increasing acidity. The result shows that the TMS 419 cultivar of *M. esculenta* exhibited growth suppression at low pH level.

**Key words:** Simulated acid rain, *Manihot esculenta*, senescence, harvest index, leaf abscission.

## INTRODUCTION

Acid rain is a major polluting agent harmful to terrestrial and aquatic ecosystems (Brimblecombe et al., 2007). It is the wet deposition that occurs when pollutants such as oxides of sulphur and nitrogen contained in power plant emission, factory smoke and car exhaust, react with the moisture in the atmosphere (Kita et al., 2004). In natural conditions, atmospheric precipitation is slightly acidic due to the dissolution of atmospheric carbon dioxide (Liu et al., 2010).

Rain that presents a concentration of  $H^+$  ions greater than  $2.5 \mu eq^{-1}$  and pH values lower than 5.6 is considered acid (Reshma and Manju, 2011). When the air becomes more polluted with nitrogen oxide and sulphur oxide, the acidity can increase to a pH value of 3. Occasional pH

readings in rain and fog water of well below 2.4 have been reported in industrialized areas. Acid deposition may cause decline in health and growth of trees as well as other plants (Wyrwicha and Sklodowska, 2006). Several experiments have been carried out in the field and in greenhouses to investigate the effect of acid rain in plants (Silva et al., 2005). Exposure of plants to acid rain results in characteristic foliar injury symptoms, modified leaf anatomy (Stoyanova and Velikova, 2004), structural changes in the photosynthetic pigment apparatus and a decrease in the chlorophyll concentrations (Sant' Anna-Santos et al., 2006).

Cassava (*Manihot esculenta* Crantz) is a woody shrub that belongs to the family Euphorbiaceae (Nweke et al.,

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2002). Since the introduction into Nigeria it has become very popular throughout the country. It is grown in 70% of the Nigerian states, available from the swamp forest area to the Guinea savannah area of Nigeria (Remison, 2005). The cassava cultivar TMS 419 is about 3-4 m tall and usually has no branching. The rain forest belt in Southern Nigeria is potentially susceptible to problems related to acid rain because of the increase in the consumption of petroleum oil products such as diesel, gasoline and coal used to produce energy for different economic sectors of the economy.

There is a need to examine the potential effects of acidic precipitation on cassava since it is a staple food in southern Nigeria for millions of Nigerians. There are over 2,000 cultivars of cassava in Nigeria (Ekanayake, 1994). TMS 419 cultivar was used for this research because it is a common cultivar found in the southern part of Nigeria. In view of the importance of this plant in human diet and the adverse effect of acid rain, the present study was carried out to assess the effect of simulated acid rain on this plant cultivar.

## MATERIALS AND METHODS

### Source of plant material

Disease free stem cuttings from matured plant of TMS 419 cultivar of *M. esculenta* were collected from the International Institute of Tropical Agriculture (IITA) Ibadan in Oyo State.

### Planting procedure

A field experiment was carried out in the school farm of the Federal University of Technology, Akure, Ondo state, Nigeria. Stem cuttings of 30 cm long each of TMS 419 cultivar of *M. esculenta* were planted horizontally with a spacing of 100 cm and four stem cuttings were planted on each row. Each pH treatment of 2.0, 3.0, 4.0, 5.0, 6.0 and 7.0 had four replicates and was arranged in a completely randomized design (CRD). The plants were watered every other day and allowed to grow for a week before the application of the simulated acid rain treatment (Reshma and Manju, 2011). Simulated acid rain was sprayed to the planted cassava cultivars every three days according to their pH values. The solutions were applied using a medium size pressurized sprayer on the plants. The plants grew for 25 weeks before the experiment was terminated.

### Preparation of simulated acid rain

The acids used were a mixture of concentrated sulphuric acid ( $H_2SO_4$ ) and concentrated nitric acid ( $HNO_3$ ) in a ratio 2:1. This is because the most important gas which leads to acidification is sulphur dioxide. The acidic solution was then calibrated using distilled water with a Deluxe pH meter to get the desired pH and cross checked with pH pen. Distilled water was used as the control of pH 7.0.

Several parameters were used in assessing the growth and productivity of the plant. The height of shoots was measured (cm) from the soil level to the terminal bud. The measurements were taken two weeks from the day the acid rain treatment commenced to the day of harvest at twenty four weeks. Leaf area was determined by the proportional method of weighing a cut-out of

traced area of the leaves on graph paper with standard paper of known weight to area ratio. The fresh and dry weights were determined after twenty four weeks of treatment. The tuber dry weight was determined by cutting the tuber into smaller pieces and drying before weighting. Relative growth rate (RGR) was calculated following the methods of Hunt (1990) and the fresh weight of the whole plant was used to determine the relative growth rate.

$$RGR = (W_2 - W_1)/(T_2 - T_1)$$

Where,  $W_2$  = final weight,  $W_1$  = initial weight,  $T_2$  = final time and  $T_1$  = initial time.

The chlorophyll content of the leaves was determined and the harvest index was determined by the method of Ekanayake (1994):

$$\text{Harvest Index (HI)} = \text{Tuber dry weight/total plant dry weight}$$

## Statistical analysis

Data obtained were subjected to analysis of variance (ANOVA) using the Statistical Package for Social Sciences, Version 15.0 (SPSS, 2003). Treatment means were separated using the Duncan multiple range test (Zar, 1984).

## RESULTS

Morphological changes were observed in TMS 419 cultivar of *M. esculenta* throughout the period of the experiment. Table 1 shows the effects of simulated acid rain on the morphology of TMS 419 cultivar of *M. esculenta* at 24 weeks after simulated acid rain treatment. Leaves turned brownish, withered with 60% leaf abscission at pH 4.0. The falling and eventual collapse of leaves stretched over a period of 16-20 weeks. At 4.0 pH treatment, leaf abscission started with the leaves at the base of the shoot falling with long petiole. Leaves were chlorotic and necrotic. At 2.0 pH treatment, the plants die from the base of the shoot and leaves had 40% leaf abscission.

The results of the plant height, leaf area, fresh and dry weights are presented in Table 2. There was a significant ( $p < 0.05$ ) decrease in the plant height, leaf area, fresh and dry weights of the cultivar with increasing acidity. The plant height, leaf area, fresh weight and dry weight were significantly higher ( $p < 0.05$ ) at the control (pH 7.0) as compared to the other acidity treatments.

The effect of simulated acid rain on the relative growth rate (RGR), the chlorophyll content and the harvest index of TMS 419 of *M. esculenta* is presented in Table 3. The cultivar had relative growth rate, chlorophyll content and harvest index at pH 7.0 as compared to the other acidity treatments. There was a significant reduction in the relative growth rate, the chlorophyll content and the harvest index with decreasing pH level.

## DISCUSSION

Symptoms of plants polluted with simulated acid rain



**Table 1.** Morphological changes observed in TMS 419 cultivar of *M. esculenta* polluted with simulated acid rain 24 weeks after treatments.

pH treatment	Observed effects
7.0 (Control)	Luxuriant growth
6.0	Plant had good growth and the leaves had necrotic dots on its surface.
5.0	Production of new leaves on the stem and at the leaf apex. Growth was retarded. There was 90% survival. Older leaves showed signs of curling and chlorosis.
4.0	The leaves were curled and chlorotic. Plant growth was stunted. Leaves were showing signs of burnt surfaces from the tip. Had 60% leaf abscission. There was 70% survival of the plant
3.0	Plants had stunted growth. The new leaves became folded, chlorotic followed by necrosis and eventually some of the plants died. 40% survival. 60% leaf abscission.
2.0	Had stunted growth. 30% survival. All the surfaces of the leaves were necrotic and curled. Had 40% leaf abscission from the base of the shoot.

**Table 2.** Effect of simulated acid rain (SAR) on the plant height (cm), leaf area (cm), fresh weight (g), dry weight (g) of TMS 419 cultivar of *M. esculenta*, 24 weeks after treatment.

pH of SAR	Plant height (cm)	Leaf area (cm)	Fresh weight (g)	Dry weight (g)
7.0 (Control)	274.20 ± 4.16 <sup>a</sup>	288.24 ± 3.25 <sup>a</sup>	782.11 ± 0.16 <sup>a</sup>	326.24 ± 0.21 <sup>a</sup>
6.0	96.12 ± 4.02 <sup>b</sup>	270.11 ± 3.14 <sup>b</sup>	638.30 ± 0.14 <sup>b</sup>	276.14 ± 0.20 <sup>b</sup>
5.0	90.13 ± 3.20 <sup>b</sup>	224.34 ± 3.13 <sup>b</sup>	420.16 ± 0.09 <sup>c</sup>	216.22 ± 0.16 <sup>b</sup>
4.0	84.30 ± 3.12 <sup>b</sup>	218.24 ± 3.10 <sup>b</sup>	354.20 ± 0.09 <sup>d</sup>	168.40 ± 0.14 <sup>c</sup>
3.0	62.34 ± 2.21 <sup>c</sup>	184.10 ± 1.24 <sup>c</sup>	228.10 ± 0.05 <sup>e</sup>	102.36 ± 0.10 <sup>d</sup>
2.0	50.02 ± 1.10 <sup>d</sup>	166.32 ± 1.16 <sup>c</sup>	114.27 ± 0.02 <sup>f</sup>	60.14 ± 0.04 <sup>e</sup>

Means followed by the same letter vertically are not significantly different at 5% level of significant by New Duncan's multiple range test for the parameters tested.

**Table 3.** Effect of simulated acid rain (SAR) on the relative growth rate ( $gg^{-1}d^{-1}$ ), chlorophyll content (mg/g) and harvest index of TMS 419 cultivar of *M. esculenta*, 24 weeks after treatment.

pH of SAR	Relative growth rate	Chlorophyll content	Harvest index
7.0 (Control)	4.2 ± 0.22 <sup>a</sup>	4.4 ± 0.20 <sup>a</sup>	0.6
6.0	3.4 ± 0.20 <sup>a</sup>	4.1 ± 0.18 <sup>a</sup>	0.5
5.0	2.6 ± 0.17 <sup>b</sup>	3.2 ± 0.14 <sup>b</sup>	0.4
4.0	1.8 ± 0.14 <sup>b</sup>	2.4 ± 0.10 <sup>b</sup>	0.3
3.0	1.4 ± 0.11 <sup>b</sup>	1.6 ± 0.07 <sup>c</sup>	0.2
2.0	0.6 ± 0.05 <sup>c</sup>	0.8 ± 0.03 <sup>c</sup>	0.1

Means followed by the same letter vertically are not significantly different at 5% level of significant by New Duncan's multiple range test for the parameters tested.

include chlorosis, necrosis, stunted growth, lesion, suppression of leaf production, leaf curling, withering of leaves, leaf abscission and even death of plants. Silva et al. (2006) found that plants exposed to low pH rain (pH 3.0) are generally slow-growing with leaf chlorosis and necrotic spot coupled with dehydration of the plants. In this study, simulated acid rain exposure caused chlorosis, necrotic lesions and leaf tip injuries at different pH levels (Table 1). Necrosis progressed from nodal region to the adjacent inter-nodal region leading to large scale leaf abscission. Marked chlorotic and marginal necrotic symp-

toms were observed at pH 4.0 and 5.0. However, this was less pronounced in comparison with pH 3.0 and 2.0. Similar symptoms were also observed by Johnston and Shriner (1985) on wheat at pH 4.3 and 2.3.

The TMS 419 cultivar of *M. esculenta* showed a decrease in growth parameters. Simulated acid rain at pH 2.0 caused burned irregular lesions on the plant leaves. It is well reported by many workers that plants sensitive to acid rain can present changes in their morphology, anatomy, physiology and biochemistry (Neufeld et al., 1985). All the plant growth parameters studied, including plant

height, leaf area, fresh weight and dry weight were reduced significantly at all acidity levels as compared to the control. The highest reduction was observed at pH 2.0 level (Table 2). The adverse effects of simulated acid rain on plant growth parameters on several crops were also observed by Evans et al. (1997), Banwart et al. (1990), Chevone et al. (1984) at pH 2.0

Photosynthetic pigments were also inhibited with respect to acidity levels. Chlorophyll content was significantly reduced by simulated acid rain treatment relative to the control at pH 2.0 and 3.0 (Table 3). The greater foliar injury noticed in plants exposed to pH 2.0 is associated with the decreased chlorophyll content and the damage to the photosynthetic apparatus. This is similar to the earlier results of Sheridan and Rosenstreter (1973) and Evans (1984). Chlorophyll reduction has been attributed to the removal of magnesium ion from the tetrapyrrole ring of the chlorophyll molecules by hydrogen ion (Foster, 1990) or increased transpiration due to acid rain (Evans et al., 1997). Recently, similar reductions of chlorophyll content by simulated acid rain were observed on many crops like mustard, radish, potato (Agrawal et al., 2005; Kausar et al., 2005; Khan and Deopura, 2005; Varshney et al., 2005).

The highest relative growth rate and harvest index that was recorded at pH 2.0 and 3.0 (Table 3) is similar to other results for cassava reported by a number of authors (Seinfeld et al., 1998; Ekanayake, 1994; Cock et al., 1977; Kawano, 1978). Harvest index is the fraction of total dry matter in the economically useful parts. In cassava, storage roots are the economic yield component. According to Iglesias et al. (1994), harvest index of 0.5-0.6 is the optimum level because at higher values of harvest index, root production decreases due to reduced leaf area, light interception and photosynthesis.

## Conclusion

The present results show that simulated acid rain with pH 2.0 and 3.0 has negative effect on the growth and yield of TMS 419 cultivar of *M. esculenta* due to reduction of photosynthesis as a result of chlorosis, necrosis and leaf abscission.

## Conflict of Interests

The author(s) have not declared any conflict of interests.

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*Full Length Research Paper*

## Valorization of waste plastic bags in manufacturing of binders for bituminous concretes for road coatings

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In 2012, Beninese landfills have quantified more than 12,000 tons plastic wastes with more than 50% of bags. The non-biodegradable nature of plastic generated an unprecedented environmental nuisance. The search for suitable solution led opting for partial recycling through construction processes. This article is devoted to characterization of new bituminous binders built of 50/70 graded bitumen to which is incorporated powder from molten waste plastic bags at 250-280 °C for road coatings/pavement. The analyzed parameters are binder's penetrability, softening point and adhesiveness, water absorption, and Marshall and Duriez stabilities of resulting bituminous concretes. The doped 50/70 graded bitumen, using plastic bags powder at 2-20% (wt/wt.mix), provided bituminous binders of better properties. The recorded results showed that the penetrability decreases when increasing plastic bags content, giving bituminous binders belonging to respective grades of 50/70, 40/60, 35/50, 30/45 and 20/30 followed by softening points increase. When the plastic bags content increased, better were these binders adhesivity. Similar trend was recorded for stability according to Duriez and Marshall on resulting bituminous concretes disclosing that the water absorption rate decrease. These obtained good performance characteristics should allow for significant reduction of the rapid degradation of classically coated roads, via extensive usage of waste plastic bags, then decongesting the established landfills here and there in Benin.

**Key words:** Waste plastic bags, bituminous binder, penetrability, softening point, adhesivity, stability; subsidence, bituminous concretes, water absorption rate, compacity.

### INTRODUCTION

A current unpleasant observation, in Beninese cities and villages, is this obnoxious spectacle offered by waste plastics littering the streets and verges, shallows and near watercourses, municipal or spontaneous landfills

and other locations or reserved places for entertainment. Several studies, either sponsored (MEHU, 2002; Lawson et al., 2008) or academic works here (RNCR, 2011; Gbèdo, 2009) and elsewhere (Ghernouti and Rabehide,

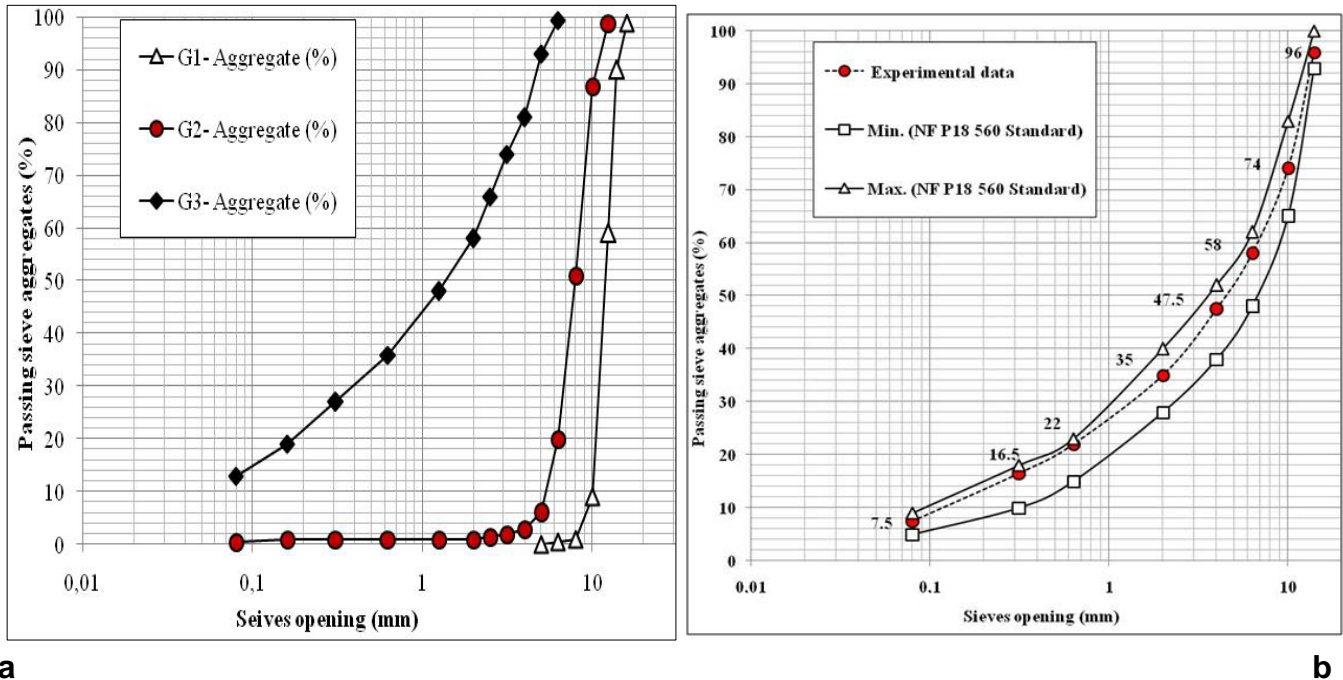
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2009; Yazoghli-Marzouk et al., 2005; Kapil and Punjabi, 2013; Vasudevan et al., 2007; Huang et al., 2007; Verma, 2008; Prasad et al., 2009), have raised this subject which became almost unbearable. According to a report from Benin Network of Resource Centers of November 2011, about 86% of the waste plastic bags are thrown on streets after use, 5.50% incinerated, 5.50% as source for cooking fire and 2.75% for various other purposes (Gbèdo, 2009). Due to the non-biodegradable nature of plastic which can withstand service life for more than 50 years, as it's said: "The plastics can stay unchanged for as long as 4500 years on earth" (Behjat et al., 2014), the recycling way, based on modern techniques, is now proving indispensable to achieve secure, healthy and sustainable environment as well, in Benin Republic, as in most of south Saharan countries. However, in majority of countries affected by this problem, technical and financial resources that could help ensuring, even a classic recycling, are practically nonexistent. Some countries, including more recently Cameroon Republic, have audaciously decided to forbid importation of non-biodegradable plastic bags. One of the identified ways as relevant to efficiently promote the waste plastics is their use in the processes of public infrastructures construction. In field, very little (almost or no) serious scientific investigations have been devoted to such recovery track in Africa. Elsewhere at contrary, fairly recent studies exist (Ghernouti and Rabehide, 2009; Yazoghli-Marzouk et al., 2005; Kapil and Punjabi, 2013; Vasudevan et al., 2007; Huang et al., 2007; Verma, 2008; Prasad et al., 2009; Behjat et al., 2014; Bindu and Beena, 2010; Khan et al., 2009; Punith and Veeraragavan, 2007; Panda and Mazumdar, 1999; Kalantar et al., 2010; IRC, 2001). Among these, can be included the one that proposed the recycling of waste plastics as incorporated materials for reinforcing the infrastructures construction, as well, for hydraulic mortars and classical concretes, after being properly conditioned by cutting them into fine particles (Aroz Sultana and Prasad, 2012; Ghernouti and Rabehide, 2009; Yazoghli-Marzouk et al., 2005), as for the bituminous concretes and paving stones for roads surfacing (Kapil and Punjabi, 2013; Jain et al., 2011; Vasudevan et al., 2006; Huang et al., 2007; Kalantar et al., 2010; IRC, 2001). The obtained results by Yazoghli-Marzouk et al. (2005) showed that the mechanical and hydraulic resistance of mortars and concretes, the water absorption and thermal conductivity decreased as incorporated percentage of plastic wastes was increased: from 2 to 50%. The method has the merit of proving the beneficial effects concerning the possibility for using plastic wastes, in large quantities in site of construction and postulating it's attractive in terms of cost (Yazoghli-Marzouk et al., 2005). Moreover, the waste plastics have been used alone (between 10 and 30 %) for coating aggregates or in combination with 80/100 bitumen class (between 1 and 10%) or mixed with tyres powder (from 1 to 5%) in the implementation of pavements coating

(Vasudevan et al., 2007). The reached results allowed the authors concluding to an increase in compressive strength and flexural strength of the obtained composites, but embedding a higher plastic content in bitumen, is not favorable. In Benin Republic, first attempts for thermally processing of the waste plastics date back a decade and are attributed to BETHESDA non-governmental organization (NGO) which has experienced pavements manufacturing by incorporating the melted waste plastics. More recently, laboratory tests were performed for mechanical characterization of a composite material made of wood-sawdust bound in mixture with molten plastic for woody furniture production (Doko, 2013). Ultimately, the largest volume of plastic bags will fail daily in municipal or spontaneous landfills where they are mixed with various other wastes. Populations have a habit of removing much for backfilling the shallows before becoming established. Farmers found that the waste plastics boots act to seal soils making them unfruitful, due to the significant decline in water infiltration that they cause. This article is devoted to study the influence of incorporation of the powder, obtained from melted of the extracted waste plastic bags from dumps/landfills, cooled and finely ground, on the performance classical characteristics of the bituminous binders and the derived concretes, chiefly their penetrability index, softening point, adhesivity, stability according to Duriez and Marshall, and slump/creep flow (Duriez and Arrambide, 1959; Jeuffroy, 1978). This choice was made in perspective of an incentive for eco-recovery, through a quantitative usage of waste plastics in construction processes (flexible pavements and other concrete infrastructures). This should contribute to a significant reduction of this established bane by proliferation of non-biodegradable waste plastic bags in Africa.

## MATERIALS AND METHODS

Materials which were the tests subject reported in this article are categorized as they follow. However, the main material was the waste plastic bags, of black color. This choice is guided by the intended use but also by color compatibility with that of used conventional 50/70 graded bitumen in construction of the roads in Benin. Thus, the used waste plastic bags surely belong to one or another of the following six (06) dominant marks from those consumed many variants on the Beninese markets: Induplast (Togo), Africa 24 (Togo), Eagle (Togo), Le nouveau (Ivory Coast), Sunshine (Benin) and Cheval (Benin). Truly employed waste plastic bags are from all comers category, but black. They consist essentially of materials made of low-density polyethylene (LDPE) that belongs to linear or branched chains thermoplastic polymers class obtained from additive reactions. The LDPE is built of interconnected macromolecules by low intensity Van der Waals or hydrogen bonds connections often represented by  $(-CH_2-CH_2-)_n$ . Its molecular weight is about  $7,000 \text{ g.mol}^{-1}$  and density  $0.92 \pm 0.01 \text{ g.cm}^{-3}$ . The LDPE overall behavior thus depends on chains mobility relative to each other and C-C bonds rotation. Under the heat action, thermoplastics, especially LDPE, melts/softens and recovers its rigidity on cooling and this mechanism is reversible. This LDPE main property, qualified elsewhere as high thermal extension but



**Figure 1.** Particles size of the used aggregates and location in relation with the recommendations of NF P18-560 standards (Editions, 1997): two extreme curves a. Particles sizes of aggregates G1, G2 and G31. b. Used aggregate mix particles size.

low stiffness (Afroz-Sultana and Prasad, 2012), has been exploited in current investigation. In practical manufacturing of LDPE plastic bags, many different additives are often added, depending on manufacturers and desired properties to be conferred on the produced bags. Similar additives were applied to derived products from high density polyethylene (Moatasim et al., 2011).

For the various tests, for penetrability and ring and ball softening point, the materials consist of 50/70 graded bitumen (as control) designated by M0 on one hand, and to this same 50/70 bitumen to which was added the powder of the melted waste plastic bags at respective contents of 2, 4, 6, 8, 10, 12, 15, 18 and 20% by weight of bitumen (partial substitution) on the other. These binder mixes were respectively identified by M<sub>1</sub> (as mixture 1 for 2%), M<sub>2</sub> (as mixture 2 for 4%) to M<sub>9</sub> as shown. For adhesivity assays, the used materials are those from the binder mixtures M<sub>0</sub>, M<sub>1</sub>, M<sub>2</sub>, M<sub>3</sub>, M<sub>4</sub>, M<sub>5</sub> and the obtained fines from crushed aggregates of sizes between 0.2 and 0.5 mm that displayed an absolute density of 2,690 kg/m<sup>3</sup>.

For Duriez and Marshall respective tests, the involved materials were the crushed granite that has been divided into three (03) gradings [G<sub>1</sub> of φ=10/14, G<sub>2</sub> of φ=6/10) and G<sub>3</sub> of φ=0/6) as shown in Figure 1.

The used sieve series belongs to that of French Standards Association (AFNOR). Openings and different percentages of theoretically expected sieves passing are shown in Table 2.

The really used aggregate derives from a made reconstitution based on the three different aggregates (G<sub>1</sub>, G<sub>2</sub> and G<sub>3</sub>) having particles size distribution structures are disclosed in Figure 1a. This reconstitution is carried out according to the recommended grading ranges by P18-560 standards as shown in Figure 1b. One can observe that the particles size distribution of the resulting aggregate (Figure 1b) is in effect well integrated within the established range for normalized particle sizes. This aggregate contains, in weight percentage, 25% of aggregate class G<sub>1</sub>, 20% of aggregate class G<sub>2</sub> and 55% of aggregate class G<sub>3</sub>. The average absolute density of these aggregates is 2,690 kg/m<sup>3</sup>.

**Procedure for preparation of powder from the waste plastic bags**

The adopted method in development of the new bituminous binder is first to melt the waste plastic bags in a suitable metal container protected against free air (oxygen) entrance. The melting process was methodically carried out with monitoring of operative temperature of 250-280°C (max). It's known that, polyethylene ignition temperature and particularly decomposition, as those of most plastic materials, occur between 300 and 350°C (Vasudevan et al., 2007). Temperature recorder TESTO (0-1000 °C, 4 outputs) equipped with K-type thermocouples was carefulness used in this regard. In Figure 2 is shown an example of acquired typical kinetics in terms of temperature during the melting and cooling phases of the powder preparation cycles from waste plastic bags. In reality, the used waste plastic bags are already melted between 200 and 275°C. This obtained liquid plastic was therefore allowed to cool in ambient air, at temperature of 29-31°C and relative humidity of 67-73%. The derived solid was then finely ground into powder for passing the 0.160 mm normalized sieve. For this, crushing and grinding of the platelets of molten waste plastic bags was operated with electromechanical miller of Ding Mill n°2A type, the same classically employed for milling of agricultural grains.

**Development of the proposed new bituminous binders**

Nine (09) different bituminous binder mixtures indexed as M<sub>1</sub>, M<sub>2</sub>, M<sub>3</sub>, M<sub>4</sub>, M<sub>5</sub>, M<sub>6</sub>, M<sub>7</sub>, M<sub>8</sub> and M<sub>9</sub> were developed (Table 1). They were made from incorporation of powder from the melted waste plastic bags, cooled and finely ground to reach particles of 0.160 mm mean diameter, in partial substitution into the chosen 50/70 graded bitumen (as main binder carrier) for all the designed bituminous binders. The explored powder rates for the melted waste plastic bags are respectively of 2, 4, 6, 8, 10, 12, 15, 18 and

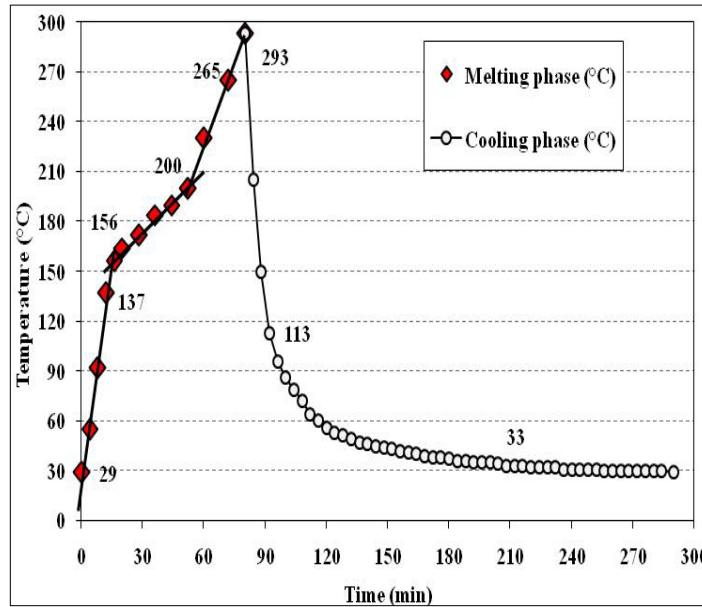


Figure 2. Recorded kinetics during the melting and cooling phases of waste plastic bags.

Table 1. Adopted percentages for constituents of tested bituminous binders mixes<sup>1</sup>.

Constituent (%)	Adopted formulation in realizing the bituminous binder mixes									
	M <sub>0</sub>	M <sub>1</sub>	M <sub>2</sub>	M <sub>3</sub>	M <sub>4</sub>	M <sub>5</sub>	M <sub>6</sub>	M <sub>7</sub>	M <sub>8</sub>	M <sub>9</sub>
Bitumen *	100	98	96	94	92	90	88	85	82	80
PMWPB **	0	2	4	6	8	10	12	15	18	20

\*50/70 graded bitumen; \*\* PMWPB, Powder of melted waste plastic bags.

Table 2. The used sieves series from AFNOR Standards and optimal theoretical granulometry.

Parameter	Value								
Sieve opening (mm)	16	14	12.5	10	8	6.3	5	4	
Percent passing (%)	100	96.5	89.5	74	65.5	55	52.5	45	
Sieve opening (mm)	3.15	2.5	2	1.25	0.63	0.315	0.16	0.08	
Percent passing (%)	41	36.5	34	26.5	19	15	10.5	7	

20% (wt/wt.mix), that of 0% corresponding to the bituminous binder made of pure reference 50/70 graded bitumen taken as control/witness and indexed M<sub>0</sub> (that is without any plastic bags powder).

The mixing of the obtained powder from the melted waste plastic bags with the chosen 50/70 graded bitumen is carried out at hot conditions: mixture temperature of 165±5°C. Preliminary investigations devoted to mastering of the optimized speed and spending time show that the use of oven-dryer at 165°C with electromechanical agitator as mixer constituted the best means for blending the grading 50/70 bitumen in progressively incorporating the powder from melted waste plastic bags. The optimized conditions were attained at relatively low speed 115±3 rpm and 18±2 min from moment it's ensured that the 50/70 graded bitumen

has entirely melted. However, trials have also been unsuccessful conducted in view of direct combining molten plastic bags to molten bitumen. The main difficulties are due to maintaining and direct mixing of fused plastic bags at melting higher temperature (250-270°C) than required for bitumen.

**Procedure in measuring binder's penetrability**

The penetrability test is performed in accordance with the procedure of EN-1426 standards. Its realization consists of releasing, for 5 s, a standardized 1.0 mm diameter needle submitted to 100 g-loading and then measuring the depth (in tenths of millimeter) to which the needle penetrates into a previously



**Figure 3.** Ring and Ball standardized testing device used for softening point measurements.

cooled bitumen (or bituminous binders mix) and maintained water immersed at temperature of 25°C and just released for this test. Penetrability Index is a quality control parameter (hardness) used for defining the class/grade of bitumen or bituminous binder in roads construction (Kapil and Punjabi, 2013; Khan et al., 2009; Punith and Veeraragavan, 2007; Panda and Mazumdar, 1999; Jeuffroy, 1978; BCEOM-CEBTP, 1975). The used bitumen, as witness (or control), in this work and for which the determined grade a priori corresponding to 50/70, was first subjected, alone (thus assumed pure), to all the realized tests, in view for protocol validation. From then on, the same tests were subsequently carried out on each the nine (09) different constituted variant mixtures  $M_1$  to  $M_9$  binders from incorporation of the powder from the melted waste plastic bags at mentioned percentages above.

The material used is conformed to that prescribed in procedure of the NF-EN-1426 standards which comprises basically: DOW brand CONTROLAB penetrometer, range values from 0 to 36 mm and its accessories; stem type thermometer range of 0 to 200°C, for monitoring the temperature of the control in view of retaining dome to the constant value equal to 25°C; stopwatch to measure the time of loading of the samples; sensitive balance to hundredth of a gram, to weigh bitumen and different proportions of realized plastic bags powder; large dimensions basin of water, devised for immersion testing of specimens; refrigerator for ice cubes producing to be used when checking thermocouples calibration; climatic chamber for maintaining or regulating the tests temperature constant to 25°C as prescribed.

#### Determination of the binders softening points

Measurement of binders softening points is made, by Ring and Ball method, according to the procedure of EN-1427 standards. The principle consists on searching for the temperature value at which any bitumen or other binder achieves a conventionally established consistency. The required equipment for this measure is the compulsory EN-1427 standards shown in Figure 3 presenting the ring and ball device used for this purpose. It comprises essentially: glass plate devoted to polish the two faces of the placed samples in rings using petrolatum; sand bath providing, without any direct

contact between the glass jar and fire, the required heat that allowing for temperature of the water that housing the rings, beads and samples, to gradually rise without exceeding a rhythm of 5°C per minute; stem thermometer, range 0 to 200°C, allowing continuous monitoring of temperature evolution; refrigerator, for ice production, ice used each time for reducing or regulating the device temperature in order maintaining rate value of 5 °C at the beginning of every test; and gas stove, for melting bitumen and filling rings on one hand and maintaining sand bath temperature, on the other.

As theoretical 50/70 graded bitumen softening point is known (EN-1427), the really acquired bitumen, as the witness/control in our done various experiences in this study, was first tested. Afterward, we became interested in the nine (09) bituminous binders  $M_1$  to  $M_9$  formed from different powder concentrations previously cited above.

#### Riedel and Weber testing method for binder's adhesivity determination

The Riedel and Weber test is performed following the procedure of NFT66-018 standards. This measurement is based on pellets of bituminous concretes, having mass of 0.50 g, formed from a bituminous binder and a crushed sand of very fine granular class (sizes 0.2/0.5 mm). These bituminous concretes in reality, are made by mixing, at appropriate temperature, 71 (mL or cm<sup>3</sup>) of aggregates and 29 (mL or cm<sup>3</sup>) of binder (made of control 50/70 graded bitumen only or one coming from the mixture of bituminous and plastic bags powder). The test consists of immersing the pellets of a bituminous concrete in the prepared respective solutions of sodium carbonate, at increasing concentrations ( $S_1$  to  $S_9$ ) in order to assess for separation degree (adhesivity encoded value) corresponding to concentration at which the binder is completely separated from aggregates. When the stripping starts at a certain concentration on a given pellet and becomes total at another concentration with another pellet, one retains as odds values, these odds corresponding to both the two concentrations scoring partial stripping and total stripping. For example, the odds value 3-5 means that the stripping began with  $S_3$  solution and was complete with  $S_5$  solution. According to normative provisions, the final odds values from 1, 2, 3 to 4 display a sufficient adhesivity, those going from 5, 6, 7, 8, 9 to 10, correspondingly, a good adhesivity and a very good adhesivity (Duriez and Arrambide, 1959). The specifications of each project should clarify the indispensable odds values (Jeuffroy, 1978; BCEOM-CEBTP, 1975). Used materials in this experimental measurements series are consistent with those for NFT66-018 standards and comprise mainly the following accessories: sensitive to hundredth a gram laboratory balance, Sarthorius type, for weighing the pellets to be tested: prescribed mass for samples, approximately 0.50 g; gas stove, for melting the 50/70 control bitumen, devised binders and also heating aggregates; Benson gas burner, for bringing the sample's carrier solution to boiling; graduated test tube, for measuring volume of other materials and another graduated test tube, arranged so that the sample, in its solution step of 6 cm<sup>3</sup>, can be brought on Benson gas burner for the normal duration of 60s, beginning from the boiling point; stopwatch, for tracking latency time set at 60 min and that of test of 60s; and distilled water and various accessories of which is the wood clamp, and the chemical reagents like different aqueous solutions of sodium carbonate (Na<sub>2</sub>CO<sub>3</sub>). Ten (10) solutions of sodium carbonate were prepared and indexed from  $S_0$ ,  $S_1$  to  $S_9$  corresponding to concentrations ranging from 0 g/L of distilled water (control/witness), 0.414, 0.828, 1.656, 3.312, 6.625, 13.25, 26.5, 53.0 to 106.0 respectively. The control 50/70 graded bitumen ( $M_0$ ) was first tested and from then on, the different variants of bituminous binder ensuing from incorporation of powder of melted waste plastic bags at different cited percentages and their decoulant bituminous concretes.

**Table 3.** Tested points in searching for optimal value of the being used binder content.

Experimented values of binder content P (%) from the determined interval (4.88%, 6.5%)										
P <sub>1</sub>	P <sub>2</sub>	P <sub>3</sub>	P <sub>4</sub>	P <sub>5</sub>	P <sub>6</sub>	P <sub>7</sub>	P <sub>8</sub>	P <sub>9</sub>	P <sub>10</sub>	P <sub>11</sub>
4.8	4.9	5.1	5.3	5.5	5.7	<b>5.8</b>	5.9	6.1	6.3	6.5

### Procedure in measurement of Marshall' stability

The test consists of compacting samples according to a defined process and then subjecting them to compression test. The used material is conformed to that prescribed by NF P98-251-2 standards. It essentially comprises of: a Marshall press brand IGM, Marshall molds and Marshall compactor (setup in this study for operating at 50 cycles), a balance of 500 g hundredth of a gram sensitive and a balance range 4000 g sensitive tenth of a gram, a stem thermometer of range 200°C, and a mercury thermometer of range 150°C, an oven-dryer of range 250°C, a stopwatch, a gas stove and a 80L thermostatically bath adjusted to 60°C.

The proportions of various constituents of bituminous mixture were determined following the formulation from a tests series to meet the set convergence criteria (stability, compactness and creep) fixed by specifications wrote by the project manager to finally evaluate the optimal dosage of each of the said constituents.

### Achievement of Duriez tests

The main object of Duriez test is to characterize the quality of the coated materials in terms of mechanical strength on the one hand and their resistance against water stripping, on the other. It is applied to bituminous coated materials and aggregates which pass entirely square mesh sieve of 20 mm. The taken sample is introduced in only one time into the glycerin pre-coated molds. The full molds pass a stay of 30 min in oven-dryer regulated to 160°C. The applied compacting load is 60 kN. This charge is maintained for 300 s. The specimen is removed from the mold after staying 240 min; time allowed to reach, by cooling at open air, the ambient temperature. During the first 24 h after manufacture, the samples are stored in a climatic chamber at constant set room temperature of 18°C. Two (02) of samples are devoted for measurements of hydrostatic bulk densities, four (04) to conservation without immersion and the remaining two (02) others to water immersion conservation. Conservations were performed in an atmosphere temperature of 18°C and relative humidity of 50%±10% by following procedure of the NF P98-251-1 standards.

### Formulation of a bituminous concrete

#### Determination of to test materials composition (NF P98-251-1)

The formulation of a bituminous concrete, dedicated to specimens confection for Duriez and Marshall tests, is commonly carried out on the basis of values of the relevant parameters such as conventional binder richness modulus ( $M_{RB}$ ), aggregates specific surface ( $\beta$ ) and absolute density ( $\rho_{AG}$ ). The conventionally adopted specific surface ( $\beta$ ) is determined, at first approximation, from relationship (Duriez and Arrambide, 1959):

$$100 \cdot \beta = 0.25 \cdot g + 2.3 \cdot S + 12 \cdot s + 135 \cdot f \quad (1)$$

Where,  $\beta$  is the aggregate of specific surface, (g) percentage of granulates greater than 5 mm diameter, S aggregates percent

having diameters between 0.315 and 5 mm, s aggregates percentage having diameters between 0.08 and 0.315 mm and (f) aggregates percentage having diameters smaller than 0.08 mm.

For this calculation, referring to Figure 1b, value of aggregates specific surface is, in case of this study, as  $\beta=12.2645 \text{ m}^2/\text{kg}$ . The binder richness modulus ( $M_{RB}$ ) is a very important characteristic. As it is said, the "Binder richness controls the flexibility of coating". It should be, neither too low, nor too high. Its value ranges between 3.50 and 3.75 in France, but can attain 6 for some non-road facilities (Duriez and Arrambide, 1959). For hot climate countries, case of Benin Republic, the prescribed values for binder richness modulus range from 3 to 4 (BCEOM-CEBTP, 1975) and 3.50 to 3.80 for high traffic roads (Coquand, 1975). We have then chosen to test the larger range values from 3 to 4 recognized to be convenient for hot climate countries (BCEOM-CEBTP, 1975). The binder content value to be considered (P%) is function of both two quality control characteristics (the binder richness modulus  $M_{RB}$  and the aggregates specific surface  $\beta$ ) and can be determined using the following formula:

$$P = M_{RB} \cdot \sqrt[5]{\beta} \Leftrightarrow \log P = \log M_{RB} + (1/5) \cdot \log \beta \quad (2)$$

The maximal binder content ( $P_{Max}$ ) is derived from equation (2) by substituting maximal value of binder richness modulus ( $M_{RBmax}$ ) where  $M_{RBmax}=4$  and the previous value of aggregates specific surface ( $\beta$ ). This leads to maximal value of binder content of  $P_{Max}=6.6\%$ .

The same calculation procedure was applied to minimal value of binder richness modulus ( $M_{RBmin}$ ) where ( $M_{RBmin}$ )=3 giving  $P_{Min}=5.0\%$ .

The normalized aggregates absolute density ( $\rho_{AG}$ ) being 2.65 and the truly used aggregates absolute density ( $\rho_{EG}$ ) in case of our tests 2.69, it is then necessary to apply a correction to this obtained binder content (P%) and consequently to  $P_{Max}$  and  $P_{Min}$ . The correction factor (k), calculated as the ratio of conventional absolute density to effective absolute density, is equal to:

$$k = \rho_{AG} / \rho_{EG} = 2.65 / 2.69 = 0.985$$

Thus, the corrected minimum and maximum binder contents  $P_{Min,cor}$  and  $P_{Max,cor}$  become:

$$P_{Max,cor} = 6.6 \cdot k = 6.6 \cdot 0.985 = 6.5\% \quad (3)$$

$$P_{Min,cor} = 5.0 \cdot k = 5.0 \cdot 0.985 = 4.88\% \quad (3')$$

Therefore, from these corrected values of minimum and maximum binder contents giving rise to interval  $[P_{Min,cor}, P_{Max,cor}] = [4.88\%, 6.5\%]$ , the binder contents that must truly be experienced were determined. To reach the latters, interval [4.88%, 6.5%] has been arbitrarily divided by adopting a sampling step which allows for obtaining 11 experimental points, with finer resolution mainly around the sketched optimal point. This has led to tested different values of the binder contents (P %) gathered in Table 3.



**Table 4.** Proportions of aggregates (types G, Sizes  $\phi$ ) and 50/70 graded bitumen with corresponding masses (g) in mixes giving the tested bituminous concretes.

Binder's optimal rate in mix (%)	Aggregates total mass in the mix (g)	Aggregates G <sub>1</sub>	Aggregates G <sub>2</sub>	Aggregates G <sub>3</sub>	Bitumen 50/70 mass (g)	Mixture total mass (g)
		$\phi$ (10-14)	$\phi$ (6-10)	$\phi$ (0-6)		
		25%	20%	55%		
6.5	1127	282	225	620	73	1200
6.3	1129	282	226	621	71	1200
6.1	1131	283	226	622	69	1200
5.9	1133	283	227	623	67	1200
5.8	1134	284	227	623	66	1200
5.7	1135	284	227	624	65	1200
5.5	1137	284	227	626	63	1200
5.3	1140	285	228	627	60	1200
5.1	1142	285	228	629	58	1200
4.9	1144	286	229	629	56	1200
4.8	1145	286	229	630	55	1200

**Table 5.** Proportions and masses for bituminous concrete constituents in Duriez tests

Bituminous concrete composition at binder content of 5.8 %				
	Type G - Size $\phi$	Percentage (%)	Partial mass (g)	Mass (g)
<b>Aggregates:</b>	G <sub>1</sub> - $\phi$ (10/14)	25	236	<b>945</b>
	G <sub>2</sub> - $\phi$ (6/10)	20	189	
	G <sub>3</sub> - $\phi$ (0/6)	55	520	
<b>Bitumen:</b>	50/70	<b>5.8</b>	55	<b>55</b>
<b>Total mass of bituminous concrete (g):</b>				<b>1, 000 g</b>

State the parameter for the values highlighted (Partial mass (g) corresponding to different cited percentages).

#### Determination of bituminous concretes composition

Total mass of the components to include in the Marshall mold, according to NF P98-251-2 for each batch, is 1,200 g. The mass of aggregates ( $M_{AG}$ ) to be considered is determined on basis of the binder content (P %) using the formula (Duriez and Arrambide, 1959; BCEOM-CEBTP, 1975):

$$M_G = (100 \cdot 1,200) / (100 + P) \quad (4)$$

Application of relation (4) leads to the listed values for proportions of both two used constituents (aggregates of type G and size class  $\phi$ ; 50/70 graded bitumen) of bituminous concretes (Table 4).

Theoretical binder contents were estimated and then used to prepare various samples of bituminous concretes subjected to tests. Classical control characteristics from realized tests, as Marshall' stability, apparent density, compactness and creep, allowed determining the bitumen optimal content. This binder ratio, identified from previous experiences as being the best, has served for calculating the respective masses of components for the different bituminous mixtures subjected to Duriez tests. Then, the retained optimal composition of bituminous concretes was disclosed in Table 5.

It should be mentioned, in this regard, that the Duriez mold only admits 1,000 g of material in case of the aggregates mixtures which larger diameters less than 14 mm (NF P98-251-1 standards) compared to Marshall's mold containing 1,200 g.

Doping of bituminous binder involves the incorporation that is replacing, weight for weight, a known percentage of the chosen

50/70 graded bitumen as control, by powder from the melted waste plastic bags. In reality, four (04) rates of dope (powder from melted plastic bags) were analyzed in partial substitution to 50/70 bitumen in the studied bituminous binders and their derived concretes. The explored powder percentages from the melted waste plastic bags are respectively of 0, 4, 8, 12 and 20% (wt/wt.mix), the (0% wt/wt. binder mix ) bituminous concrete corresponding to non doped 50/70 graded bitumen (as control), thus being a total of explored five (05) points in this series of effected experiences. In Table 6 are gathered constituents corresponding masses of different binder mixes percentages for various tested Asphalt concretes specimens for Marshall and Duriez testing methods.

#### Processing and analysis of the recorded data

The acquired data from those different realized experiments were statistically processed using Microsoft Excel software 2010 editions. It allows analysis, exploration and identification of the mathematical models that describe the behaviors of recorded data and corresponding trends' curves.

## RESULTS AND DISCUSSION

### Results from penetrability measurements on the selected binders

The recorded data during penetrability tests are summa-

**Table 6.** Summary of Asphalt concretes mixes as function of plastic bags powder percentages.

Asphalt concretes constitution at binder optimal rate	Powder percentages and corresponding values in used binder mixes total mass for tests in:												
	Unit	Marshall method						Duriez method					
Binder optimal rate	%	<b>5.80</b>											
Aggregates total mass	(g)	1,134						945					
Plastics rate in binder	%	0	4	8	12	20	100	0	4	8	12	20	100
Bitumen 50/70 mass	g	66	63.36	60.72	58.08	52.8	0	55	52.8	50.6	48.4	44	0
Plastics powder mass	g	0	2.64	5.28	7.92	13.2	66	0	2.2	4.4	6.6	11	55
Binder mix total mass	g	66						55					

State the meaning of these highlighted (5.80%: binder optimal rate; 1,134 g and 945 g: aggregates total mass in Marshall and Duriez methods; 66 g and 55 g are respective binder mixes total masses in 1,200 g and 1,000 g samples' masses).

**Table 7.** Results from penetrability tests for the constituted bituminous binders' mixtures.

Tested Bituminous binders' mixtures	Powder from melted of waste plastic bags contents (% w/w.mix)	Measured Penetrability values ( $\times 10^{-1}$ mm)						Obtained range values ( $\times 10^{-1}$ mm)	Rounded mean values ( $\times 10^{-1}$ mm)	Corresponding penetrability indexes ( $\times 10^{-1}$ mm)
		Series 1			Series 2					
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
M <sub>0</sub>	0	64	56	61	62	56	65	56-65	61	50-70
M <sub>1</sub>	2	59	54	60	59	55	54	54-60	57	50-70
M <sub>2</sub>	4	51	53	55	55	52	51	51-55	53	40-60
M <sub>3</sub>	6	49	46	47	47	50	48	46-50	48	40-60
M <sub>4</sub>	8	44	45	42	46	43	44	42-46	44	35-50
M <sub>5</sub>	10	37	40	41	39	39	41	37-41	40	35-50
M <sub>6</sub>	12	33	35	32	32	34	35	32-35	34	30-45
M <sub>7</sub>	15	27	28	26	25	27	26	25-28	27	20-30
M <sub>8</sub>	18	23	21	22	22	23	22	21-23	22	20-30
M <sub>9</sub>	20	20	19	19	19	19	20	19-20	19	Out of standards

ized in Table 7.

The powder content was based on weight of waste plastic bags to weight of binder mix (50/70 bitumen + waste plastic bags powder). Analysis of these results showed that the incorporation of powder, from molten plastic bags, cooled and finely ground, at explored range contents, from 0 (M<sub>0</sub>) to 20% (M<sub>9</sub>), has a significant influence on penetration index of the resulting binder mixes. Indeed, in this Table 7, the obtained values (columns 3 to 8) were translated into ranges (column 9) and average values (column 10). In column (11) were displayed the five (05) classes to which belong different realized binder mixtures on the nine (09) bitumen classes as defined by the EN-1426 standards. Thus, the binder mixtures indexed M<sub>0</sub> to M<sub>1</sub> and M<sub>2</sub> to M<sub>3</sub>, M<sub>4</sub> to M<sub>5</sub>, M<sub>6</sub> and M<sub>7</sub> to M<sub>8</sub> correspond to bituminous binders of the respective five (05) following classes: 50/70, 40/60, 35/50, 30/45 and 20/30. The obtained value for binder mixes penetrability, at waste plastic bags powder content of 20%, leads to conclusion that, the corresponding bituminous binder M<sub>9</sub> exits from the known conventional

grading roads bitumens. It rather enters the special grading bitumen of penetrability classes of 10/20 and 15/25 devoted to development of the high modulus asphalt concretes (HMAC). According to French Professional of Asphalt Group specialists, these two last grading bitumens rather provide answers to the caused problems by unexpected increase in heavy traffics. The recorded behavior for M<sub>9</sub> bituminous binder has practically indicated that, incorporation of more percentage of plastic bags powder, than 20%, in substitution for 50/70 graded bitumen in the course for designing bituminous binder's mixes, can be excluded from targeted blending. These results well corroborate the ones attained by Vasudevan et al. (2007) who worked on other kind plastics and 80/100 graded bitumen and recorded similar tendency but at more low plastic content (0 to 10%) than ours (0 to 20% wt/wt. binder mix). Similar results have been obtained by Jain et al. (2011) using the waste polymeric packaging materials. Conclusion was made that, all the designed binder mixes in current study, corresponding to five (05) on the known pure nine (09)

**Table 8.** Results of softening point measurements for tested binder mixes.

Testing ball (diameter) (mm)	Bituminous binders mix and corresponding softening points (°C)							
	M <sub>0</sub>	M <sub>1</sub>	M <sub>2</sub>	M <sub>3</sub>	M <sub>4</sub>	M <sub>5</sub>	M <sub>6</sub>	M <sub>7</sub>
Ball 1 (9.35)	36	41	41	41	43	43	50	> 110
Ball 2 (9.35)	37	42	43	43	44	45	51	> 110
Mean-value (°C)	36.5	41.5	42	42	43.5	44	50.5	> 110

**Table 9.** Adhesivity odds values related to added powder percentage of melted plastic bags.

Bituminous mixtures	M <sub>0</sub>	M <sub>1</sub>	M <sub>2</sub>	M <sub>3</sub>	M <sub>4</sub>	M <sub>5</sub>
Adhesivity levels / odds	2-10	5-10	5-10	6-10	9-10	>10

grading bitumens for road coatings, can be substituted to the latters from their penetrability index viewpoint.

### Results from softening point measurements of constituted binders

In analyzing the recorded values during effected measurements and reported in Table 8, it can be noted that, obtained value of softening point for the used 50/70 bitumen as control is relatively low (36-37°C) compared with that for true 50/70 graded bitumen. According to requirements of EN-1427 standards, softening point of grading 50/70 bitumen should normally lay between 46 and 54°C. Therefore, we thought that this observed difference (10-17°C) could be explained, either by improper quality or supply source, as well as the storage conditions of this 50/70 bituminous binder material prior to its admission in our laboratory. It is especially important to emphasize that, till now, the bitumens market is known to belonging to a rather protected professional sector, mainly with regards to the developing countries.

The used 50/70 witness/control bitumen in this study may thus not be exactly that truly normalized or accordingly, has already been probably aged to some extent in stock, at delivery time. However, it's found that, in global way, results from the carried out tests show that softening points of decoulant bituminous binders increases as the added percentage of waste plastic bags powder increases. These results well corroborate those published elsewhere (Jain et al., 2011; Garcia-Morales et al., 2006; Vasudevan et al., 2007, Sadeque and Patil, 2014) in which similar trends had been observed. The bituminous binder (M<sub>7</sub>), containing 15% (by mass of plastic bags), has disclosed value of softening point exceeding admissible conventional limits (>94°C) using experimental water bath (80°C according to standards prescriptions). When making use of glycerol bath which allows to reach temperature of 110°C, the two testing balls then dropped in perforating the samples without softening the blended bitumen disc. The experiments

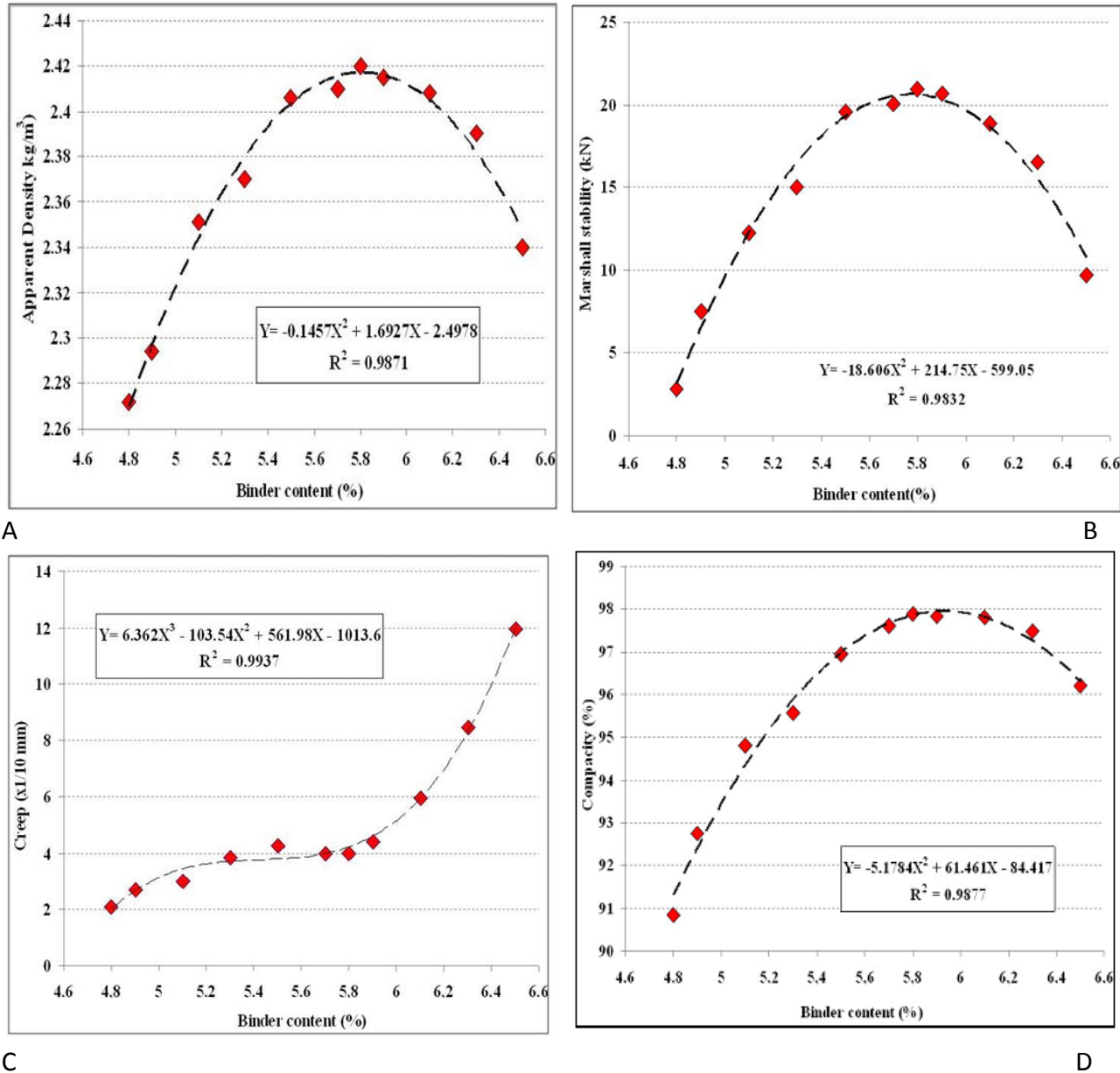
series were then stopped to M<sub>7</sub> due to test temperature forthcoming that of glycerol's flash point which is around 160°C. This behavior clearly shows that the mix binder M<sub>7</sub> has very high consistency. Conclusion that can drawn at this step is that, incorporation of powder from the melted waste plastic bags to used 50/70 graded bitumen recovering binder mixes possessing softening point values reasonably closer to that for true 50/70 graded bitumen and subsequently having its performance from this point of view.

### Results from adhesivity measurements for constituted binders

The values of recorded odds during adhesivity measurements were those summarized in Table 9. Analysis of these results led to conclusion that the incorporation of the melted waste plastic bags powder to conventional 50/70 graded bitumen affected, in positive way, ability of the derived binder mixtures to well adhere to aggregates: from 2-10 for M<sub>0</sub> (50/70 bitumen), through M<sub>1</sub>, M<sub>2</sub> to 9-10 (M<sub>4</sub>). This conclusion is evidenced by the fact that, there has been an increase in value of adhesivity odds with increasing the melted waste plastic bags powder content. The solution of S<sub>2</sub> concentration has spawned the beginning of stripping of the witness/control bitumen and with the S<sub>9</sub> solution, the obtained stripping was only partial.

All other bituminous mixtures have opposite a resistance to a pickling by solutions from the concentrated to highly concentrated, at point where no possibility exists to observe a stripping start prior to intervention of S<sub>4</sub> solution. The total stripping has therefore not been recorded, even with the most concentrated solution.

However, the realized pellet of bituminous binder and subjected to the conducted tests, after which the score 10 is reached for binder M<sub>0</sub>, has seriously been degraded, while the pellets from mixtures M<sub>4</sub> and M<sub>5</sub> (>10) have experienced no detectable degradation following application of the same solution S<sub>9</sub>. These results clearly show that the incorporation of the melted waste plastic bags



**Figures 4.** Evolutions of Apparent density (A), Marshall' stability (B), Creep (C) and Compacity (D) of the tested bituminous concretes as function of percentage of control 50/70 graded bitumen ( $M_0$ ).

powder to conventional 50/70 graded bitumen  $M_0$  permit augmenting adhesivity of decoulant binders and subsequently their quality in terms of binders extractible rates for the derived bituminous concretes.

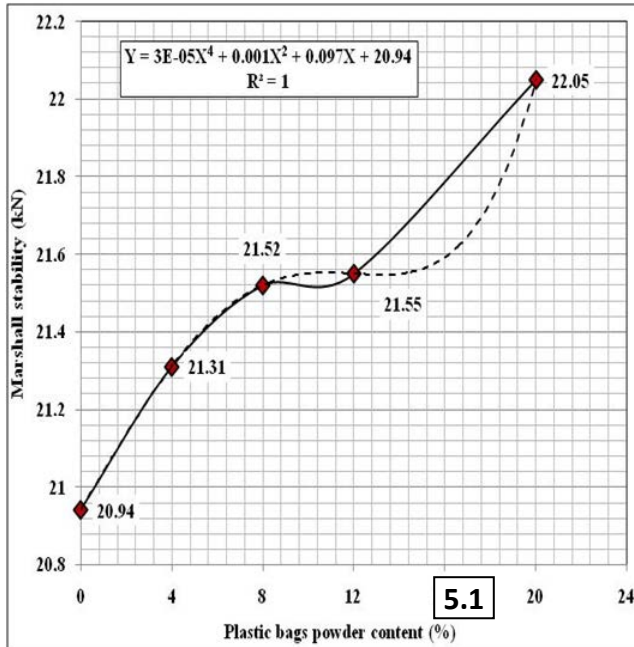
**Results from determination of bituminous binder optimal content**

The results of various tests carried out for determination as well as, Marshall stability, apparent density, subsidence, creep, as that of voids rate (not shown), as function of the reference bituminous binder  $M_0$  content (P

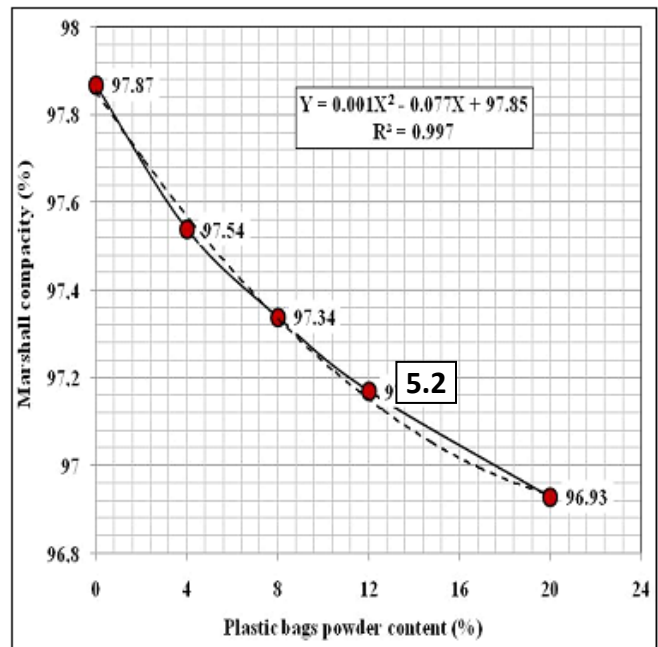
%) in interval from 5.5 to 6.1%, are shown in Figure 4.

Analysis of these tests results allowed determining the optimal rate of bituminous binder dosage which was almost established to a value of 5.8%. Indeed, the deployed data on these figures clearly showed that this optimal value of 5.8% for  $M_0$  binder content correspond those of maximal Marshall stability of 20.94 kN, maximal apparent density of 2.42 kg/m<sup>3</sup> and minimal creep of 3.997x1/10 mm. The latter is well located within the range of recommended values [2x1/10; 4x1/10mm] by Asphalt Institute for heavy traffics Roads Pavement (Bindu et al., 2010; Khan et al., 2009).

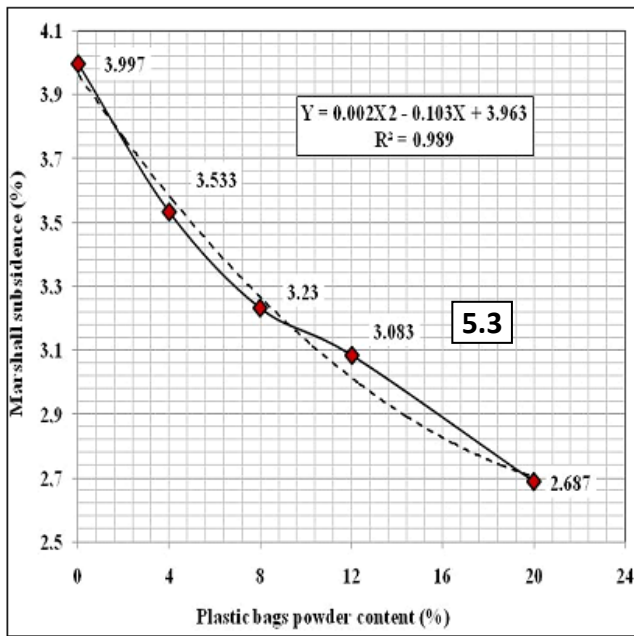
After apprehending the revealed behavior by each of



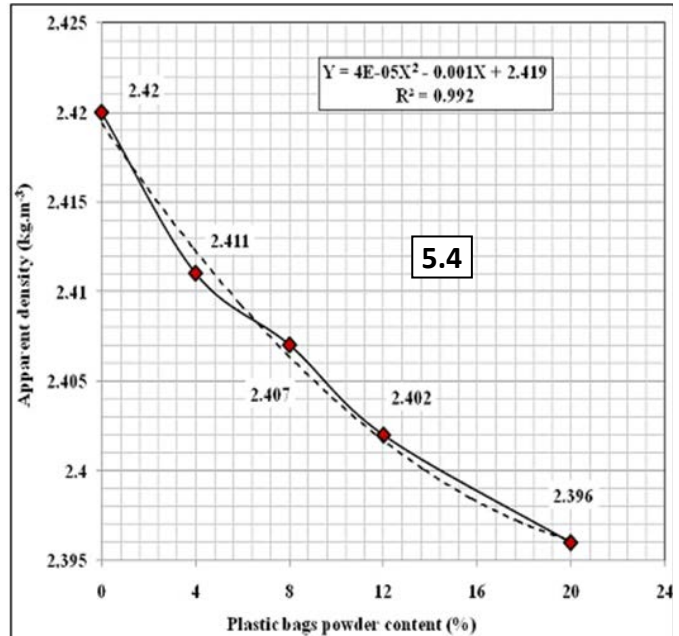
A



B



C



D

**Figure 5.** Effects of the added molten plastic bags powder contents on Marshall' stability (A), Subsidence (B), Compacity (C) and Apparent density (D) of doped bituminous concretes (solid lines = experimental data curves; dash lines = trend curves).

these characteristic parameters in case of chosen pure 50/70 graded bitumen ( $M_0$ ) as control, the tests were then realized using the mixed binders made of incorporated powder from molten waste plastic bags into the grading 50/70 bitumen, as well as their derived bituminous concretes (the final Asphalt materials for road coatings/pavements). The results of these done experimental measurements were those embedded in Figure 5.

**Analysis of results of Marshall's tests on bituminous - plastic bags powder concretes**

Remember that the tested powder contents for the melted waste plastic bags in this series were 4, 8, 12 and 20%. The powder content was based on the weight of melted waste plastic bags to the weight of mix binder (50/70 graded bitumen + waste plastic bags powder).

They correspond to the plastic bags powder incorporated bituminous binders previously identified respectively as  $M_2$ ,  $M_4$ ,  $M_6$  and  $M_9$ . In view of performances comparison, obtained results were faced against those from pure bitumen binder ( $M_0$ ).

### Effects of plastic bags powder content on bituminous concrete bulk density

In Figure 5a shows the results for evolution of the bulk density of bituminous concrete made of bitumen doped in plastic bags powder. It clearly shows that the bulk density of the bituminous concrete decreases as the powder content of introduced molten waste plastic bags into 50/70 graded bitumen increases from 0 to 20% although variation of the density appear relatively low: less than 1% (exactly 0.99%) against a theoretical variation, based on the used bitumen as a control ( $M_0$ ) of 0.58%. These results well corroborate the observed trend elsewhere in working on the mixture of cement mortar and plastic composite (Yazoghli-Marzouk et al., 2005). The polynomial function that adequately fits the data from the evolution of apparent density (Y) versus the molten plastic bags powder content (X) may be represented by the tendency equation expressed as:

$$Y = 100.9 \cdot X^4 - 39.84 \cdot X^3 + 5.213 \cdot X^2 - 0.376 \cdot X + 2.42 \quad (5)$$

With a regression coefficient value of:  $R^2 = 1$ .

### Effects of plastic bags powder content on Marshall' stability of bituminous concretes

The recorded results, from evolution study on the Marshall stability of blended Asphalt concretes using powder of waste plastic bags, are shown in Figure 5b. These exposed data allow concluding that Marshall' stability of this developed bituminous concrete increases with rising of the molten plastic bags powder content. Similar results have been recorded using Styrene Butadiene Styrene (SBS) polymer modified bituminous mixes on fatigue performance of roads (Gupta and Veeraragavan (2009) and the waste plastic polymers (Sadeque and Patil, 2014).

Indeed, it is noteworthy that the rate of change of the Marshall stability is about 5.03% against a theoretical rate of change of 9.89% corresponding to percentage content values of powder incorporation of melted plastic bags from 0 to 20%. The polynomial function that adequately fits the data from behavior of the Marshall stability (Y) of studied materials versus variation of added powder content from melted plastic bags (X), can be represented by the obtained trend equation:

$$Y = 390.6 \cdot X^3 - 120.9 \cdot X^2 + 14.14 \cdot X + 20.93 \quad (6)$$

with a regression coefficient of almost equal to:  $R^2=0.997$ .

This is a polynomial function of degree 3 admitting an inflection point around value of waste plastic bags powder content  $X = 10\%$ .

### Effects of plastic bags powder content on bituminous concrete creep

The recorded results, during realized measurements from the Marshall creep's assays on built bituminous concrete specimens from the obtained powder by grinding of the plastic bags wastes melted, bitumen 50/70 and aggregates, are presented in Figure 5. The evolution of these data clearly shows that the values of bituminous concrete creep decreases significantly when increasing the molten plastic bags powder content. Indeed, the rate of change of creep, by calculating the difference between the extreme values multiplied by one hundred divided by that of the control gives about 32.77% against theoretical rate variation of 32.82% for a contents' range of plastic bags powder from 0 to 20%. Both these obtained two rates thus are almost the same order of magnitude: the difference only about 5%.

The polynomial function that adequately fits the data from the creep evolution (Y) versus the molten plastic bags powder content (X), may be represented by the trend equation expressed as:

$$Y = -242.7 \cdot X^3 + 91.94 \cdot X^2 - 15.24 \cdot X + 4 \quad (7)$$

with a regression coefficient equal to  $R^2=0.999$ . It's also a polynomial function of degree 3 admitting an inflection point around the value of plastic bags powder content of  $X=10\%$ .

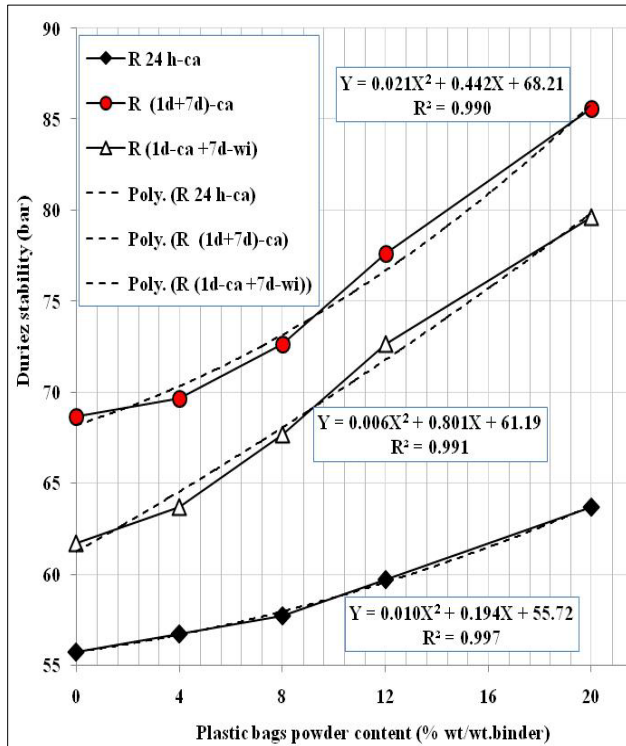
### Analysis of results of Duriez tests on doped bituminous concrete using plastic bags

Like the achieved measurements in Marshall tests, the done Duriez tests use identical bituminous binders made of powder from the melted waste plastic bags incorporated into aggregates at contents of 4, 8, 12 and 20% (blended binder weight) corresponding to the indexed respective binders  $M_2$ ,  $M_4$ ,  $M_6$  and  $M_9$ . The control bituminous concrete (0%) remains unchanged: that from the 50/70 graded bitumen ( $M_0$ ).

However, it must be underlined that additional experiences have also been performed using specific binder consisting of the pure molten plastic bags powder only, being four (04) mixes, the control (0% or  $M_0$ ), plus additional pure plastic samples.

### Results of Duriez stability measurements

The results for evolution study of the three (03) tested versions of Duriez stability are those gathered in Figure 6. Note that the Duriez stability three versions consist on determination of respective resistances of the designed bituminous concretes: first, after 1-day storage at tempe-



**Figure 6.** Evolution of Duriez stability of built bituminous concretes versus their molten plastic bags contents: R24h-c.a: on the controlled air (c.a) for 24 h; R(1d+7d)-c.a: on controlled air (c.a) for 8 days; R(1d-c.a+7d-w.i): 1-day on controlled air + 7-days water immersed (w.i) at 18°C.

perature of 18°C on the open-air (called as controlled air); second, after 8-days storage at temperature of 18°C on the open-air; third, 1-day storage at controlled air completed with size-days water immersing at temperature of 18°C.

#### **Duriez stability of bituminous concretes after 1-day of controlled air storage**

It can be observed that the Duriez stability of the bituminous concrete samples, stored 24 hon the air, increases with augmentation of their plastic bags powder content (Figure 6). It should be noted that the rate of change of Duriez stability is around 14.28% for incorporation range of plastic bags powder contents from 0 to 20%. The polynomial function that adequately fits the data from the behavior of bituminous concrete resulting data from Duriez stability study after 24 hours air storage

(Y) versus the melted waste plastic bags powder content (X), may be expressed by following trend equation:

$$Y = 0.0103 \cdot X^2 + 0.1949 \cdot X + 55.721 \quad (8)$$

with a regression coefficient value of almost equal to:  $R^2=0.998$ .

It is a parabolic branch function with concavity facing up-

wardly which minimal value being that of the obtained bituminous concretes from reference bitumen  $M_0$  freed of plastic bags powder.

#### **Duriez stability of bituminous concretes after 8-days of controlled air storage**

At 8-days aged, following preservation on the air at temperature of 18°C, the Duriez stability of bituminous concrete samples increases with rising of the molten plastic bags powder content (Figure 6). The rate of change of Duriez stability values is about 24.64% for incorporation range of plastic bags contents from 0 to 20%. The polynomial function that adequately fits the data from behavior of the studied Duriez stability on the bituminous concretes after 08 days preservation on the air (Y), versus the melted plastic bags powder content (X), may be expressed by the trend equation:

$$Y = 0.0219 \cdot X^2 + 0.4429 \cdot X + 68.214 \quad (9)$$

with a regression coefficient value of almost equal to:  $R^2=0.990$ . Here, we also find a satellite branch concavity facing upwards, the minimum value being that of bituminous concrete from control 50/70 graded bitumen ( $M_0$ ) freed of powder from melted waste plastic bags.

#### **Duriez stability at 1-day on controlled air following by 7-days water immersion**

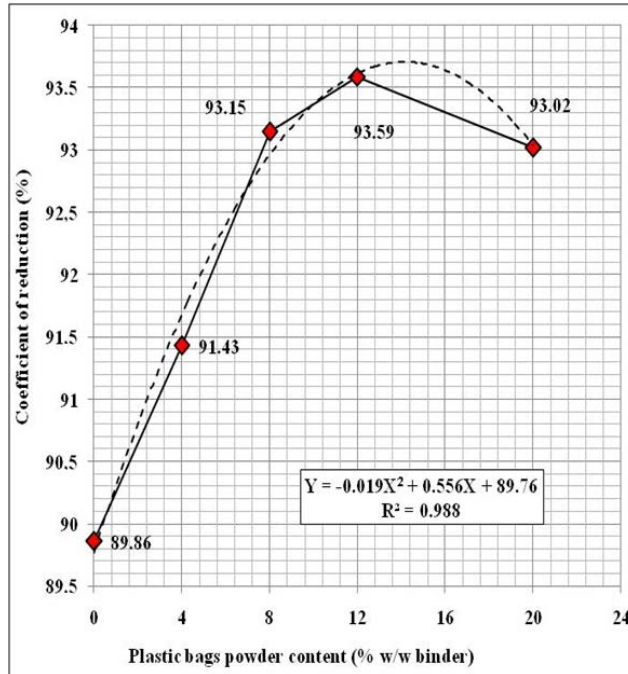
At 8-days aged, with storage for 24 h on the air at a temperature of 18°C completed with 7 days of water immersion at the same temperature, the bituminous concrete stability is experiencing growth with increasing the powder content of molten plastic bags (Figure 6). The rate of variation of Duriez stability is about 29.04 % for incorporated content values of plastic bags powder going from 0 to 20%.

The polynomial function that adequately fits the data from the behavior of Duriez stability of bituminous concretes on the air at 01-day and 7-days water immersed (Y), versus the powder content of molten plastic bags (X), can be described by the trend equation:

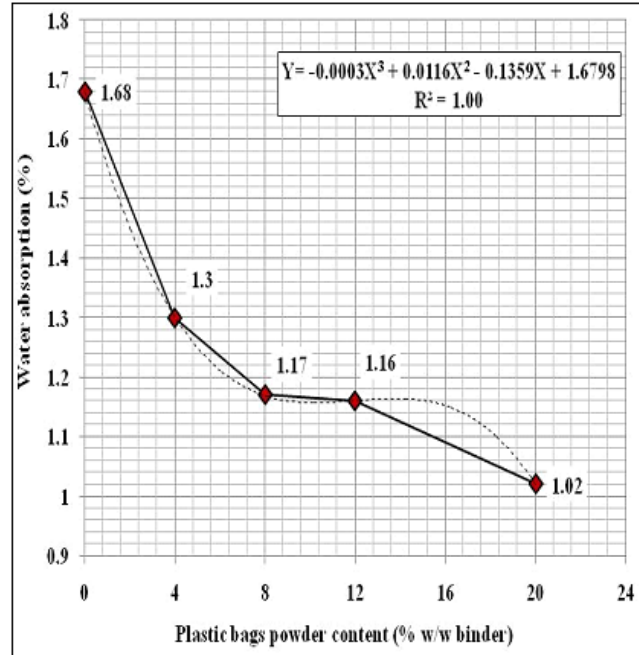
$$Y = 0.0066 \cdot X^2 + 0.8014 \cdot X + 61.195 \quad (10)$$

With a coefficient of regression equal to:  $R^2=0.991$ .

Here again, a parabolic branch function with concavity facing upwards was obtained, the lowest value being that for bituminous concrete from pure 50/70 graded bitumen binder ( $M_0$ ) freed of powder from the melted waste plastic bags. Ultimately, these results clearly lead concluding that, all forms of the determined Duriez stability for the designed bituminous concretes displayed growth as the waste plastic bags powder content is experiencing an



A



B

**Figure 7.** Duriez testing results: respective behaviors for water absorption rate at (1-day in controlled air + 7-days water immersed at 18 °C) (A) and reduction coefficient (B) of bituminous concretes versus plastic bags powder content.

increase in the studied range values of 0 to 20 % (wt/wt mix binder). In analyzing these data, at global level, one observes that, more bituminous concretes matured, from 1 to 8 days, either on the controlled air or in water immersion state, more their Duriez stability increases. At identical plastic bags powder contents, values of the provided Duriez stability by the immersed specimens in water for seven days, after spending 24 h on the controlled air, are much lower than those for not water immersed. Differences in recorded values for purpose ranged from 5.97 to 6.97 bars corresponding to an increase in resistance of 7.5 to 11.30% with reference to those from water immersed specimens.

**Results for water absorption rate of the developed bituminous concretes**

From the 7-days water immersion, following the 24-h aged on controlled air, as prescribed by standards procedure, the recorded experimental results showed a decrease of rate for water absorption of the tested specimens from bituminous concretes as percentage of powder from melted waste plastic bags increases (Figure 7a).

Recommended rate values of water absorption for aircraft runways and highways are less than 4% (Duriez and Arrambide, 1959). The chosen 50/70 graded bitumen and used alone as witness/control main bituminous binder, already met this requirement with a water

absorption rate of 1.68%. The incorporation of a water repellent into bituminous concrete, as case of powder from the melted waste plastic bags, has permitted obtaining a significant improvement in terms of reduction of the water absorption rate. Definitely, these experimental results have clearly shown that incorporation of plastic bags powder improves the water resistance by reducing its water absorption rate to 1.16% at 12% plastic bags powder content (wt/wt mix basis). At 20% plastic bags powder content, the water absorption rate of these doped bituminous concretes falls to 1.02%, corresponding to a reduction ratio of about 39.3% with reference to value for non doped 50/70 graded bitumen (1.68%).

This significant reduction of water absorption rate has been attributed to incorporated plastic bags material which has therefore permit a partial sealing of the porous structure of bituminous concretes by generating some excrescences through the aggregates boundaries, favoring the plugging of borrowable passages by water between grains of aggregates. This must constitute a qualitative good performance if the coating of roads has efficiently been realized with a firmed application of the suggested new binders.

**Results from coefficient of reduction measurements for bituminous binder mixes**

The test results show that the control 50/70 graded



bitumen alone has already achieved a reduction coefficient of 89% (Figure 7a) indicating that the quality of this chosen control bituminous binder is not so bad from this point of view. Moreover, the shown data in this figure clearly indicate that the incorporation of powder from the melted waste plastic bags has contributed to some performance improvement of the explored characteristics for bituminous concretes: from 91 to 93.5 %. Indeed, the reduction coefficient, defined as 100 times the established ratio between resistance (R') in compression after storage on the air at 18°C for 1 day completed with 7-days water immersion and resistance (R) in compression for 8-days maintain at 18 °C at open-air, is an important parameter that reflecting the influence of water soaking the bituminous concretes on their resistance. Commonly prescribed in specifications in form of R'/R (> 0.70), it's specifically recommended R'/R values greater than 0.80 (R'/R > 0.80) for aircraft runways and highways, and relatively lower values of R'/R > 0.65 for secondary roads.

On light of previous recommendations, the derived bituminous concretes, from the incorporation of powder from the melted waste plastic bags, exhibited significantly higher values of R'/R as shown in Figure 7 (Right side): from 0.899 to 0.936. It then follows quite interesting and promising experimental results that must encourage the professionals in site to adopt such the designed bituminous binders for the road coatings or pavements.

The polynomial that adequately fits the data with respect to displayed behavior by the bituminous concretes' reduction coefficient (Y), as the incorporated powder content (X) of the melted waste plastic bags varies, is a polynomial function of second degree (Figure 7):

$$Y = -0.0197 \cdot X^2 + 0.5568 \cdot X + 89.766 \quad (11)$$

with a regression coefficient value of:  $R^2=0.9888$ .

Its first derivation leads to the following equation:

$$dY / dX = -0.0394 \cdot X + 0.5568 \quad (12)$$

It vanishes and changes sign around maximal value of plastic bags powder content of  $X=14\%$ , corresponding to reduction coefficient value of  $Y=93.7\%$ . In fact, it can be remarked that the value of (dY/dX) for  $X=14.13197969$  is  $2.10^{-10}$  whilst for  $X=14.13197970$ , the taken value by (dY/dX) is  $-2.10^{-10}$ .

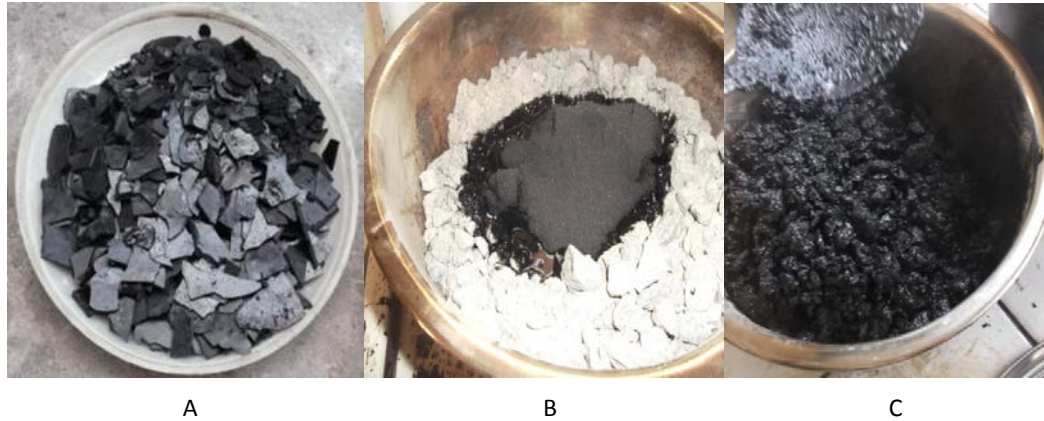
In a quest of higher performance, where the reduction coefficient is sought a priori, the decline of trend curve is questionable. However, let just closely observing the values of Duriez stability that lead to calculation of the reduction coefficient. Already, from about 9.5 % incorporated powder from the melted waste plastic bags (Figure 6), the acquired resistance after water immersion (R') is 69 bar and begins to exceed that for Asphalt con-

cretes made of 50/70 graded bitumen ( $M_0$ ) without any water immersion ( $R=68.67$  bar). At plastic bags content of  $X=11\%$ ,  $R=70$  bar and at  $X=12\%$ ,  $R=72.65$  bar. Therefore, it cannot be there a counter-performance at all. It must be understood that the new doped binder using plastic bags powder escapes the defined frame of established laws for the reference 50/70 bitumen. This revealed behavior, by the doped bituminous concretes using powder from the melted waste plastic bags, offers greater resistance on Duriez testing and more satisfactory operation than that from bituminous concrete prepared on basis of the reference 50/70 graded bitumen only, in the identified range values of waste plastic bags content: from 9.5 to 14%. The experimental results show that the range of high values of reduction coefficient, from 93.15% to maximum of 93.7%, corresponding to those of powder contents, from 8% to maximum of 14%, is advantageous for processes of road coatings. Further investigations are therefore needed with the purpose of well marking the required range concentrations and subsequently for better refining these achieved results, if the proposed orientation for recycling waste plastic bags (in quality of dope for 50/70 graded bitumen), should eventually integrate infrastructural construction habit, particularly in building of roads in Benin country.

#### Analysis of results from subsidence rate measurements

The subsidence, also called creep, measures the height deformation in breaking of a test specimen. For bituminous concretes, the limit of good performance for creep flow, one of these Asphalt concretes quality parameters, is 5% (Duriez and Arrambide, 1959; BCEOM-CEBTP, 1975). Excess creep flow is the expression of the lack of stability resulting in the risk of deforming under the traffic effects. The bituminous concrete, based on pure 50/70 graded bitumen binder, provided a determined value for subsidence rate of  $5.95 \pm 0.07\%$  (Figure 5c) higher than this prescribed limit of 5%. It is a true indication that this classically used 50/70 graded bitumen in Benin presents an obvious risk of deformation for the coated or paved roads under traffic. The experimental results, from doping of the same 50/70 bitumen, by incorporating the powder of the melted waste plastic bags, have shown significant reduction of the subsidence rate for these prepared composites. This diminution should thus allow avoiding the risk of high values of subsidence rate. Undeniably, the results showed that, for a content of 8 % (by weight) of incorporated plastic bags powder, the rate of subsidence of bituminous concrete has set to 4.47 %. Better, in grading plastic bags to 20%, the rate of subsidence decreased to 3.35% (Figure 5.3).

These results corroborate obtained similar trends of deformation reduction elsewhere (Jain et al., 2011; Prasad et al., 2009). From the shape of this results curve,



**Figure 8.** The plastic bags powder used alone as binder for concretes: platelets of the melted waste plastic bags (A), melting of powder on aggregates (B) and decouplant concrete ready to be molded (C).

one can deduce that the deformation of the Asphalt concretes under applied stress decreases with rising of the powder content of the melted waste plastic bags. A polynomial function that adequately fits the data from the developed behavior, by the bituminous concrete subsidence ( $Y$ ) versus change in powder content ( $X$ ) of the incorporated plastic bags, is also of second order expressed as:

$$Y = 0.0048 \cdot X^2 - 0.2244 \cdot X + 5.9202 \quad (13)$$

With a value of regression coefficient of  $R^2=0.9982$ .

This is an interesting proof of quality improvement for bituminous concretes which can stimulate the adoption of devised process consisting of incorporation of the powder from the melted waste plastic bags as binder for coating of roads. It should be awful, mainly for the well-known case of Benin Republic, where the built roads frequently plagued to slumps/subsidence which rather proved disastrous for the durability of this infrastructural construction.

#### **Study results on concretes using powder from pure plastic bags as binder**

In order to potentially encourage massive usage of plastic bags powder, the latter was tested alone as pure binder (100%) in manufacture of what we call "non-bituminous concretes". To do this, the same formulation as that for pure reference 50/70 graded bitumen ( $M_0$ ), the aggregates composition and even the value of modulus of richness in binder of 5.8%, was adopted. The photographs of Figure 8 show, platelets of the melted waste plastic bags (a), while at the middle, the powder melts on the aggregates (b), and on right side, the bound concrete using powder from the melted waste plastic bags" after mixing (c). The recorded results from the various Marshall

and Duriez testing, on specimens from bound concretes using the pure powder of melted waste plastic bags, instead of grading 50/70 bitumen, are gathered in Tables 10 and 11 respectively. Analysis and comments of these collected data are carried out in the paragraphs to follow.

#### **Results from Marshall' stability test for concretes from pure melted waste plastic bags**

From these shown data in Table 10, which is a typical template for Marshall testing results, it can be concluded that:

The Marshall stability, for concretes made uniquely of molten plastic bags powder, is 1.80 times the stability of bituminous concrete from 50/70 graded bitumen and only 3.14 times the conventionally prescribed value of 12kN by specifications; The Duriez stability in controlled air at 8-days aged, for concretes made of plastic bags powder, is 1.87 times the stability of bituminous concrete from 50/70 graded bitumen and only 2.57 times the prescribed value of 50 bar by specifications; The Duriez stability value for bituminous concretes made of pure plastic bags powder only, preserved for 1-day on the controlled air and water immersed for 7 days, is 1.53 times the recorded stability value for Asphalt concretes from 50/70 graded bitumen and only 2.70 times the prescribed value of 35 bar by specifications. It follows, from stability of bituminous concrete viewpoint, that the powder of melted waste plastic bags, used alone as a binder, can give to bituminous concrete more efficient characteristics than that provided by 50/70 graded bitumen alone. It may be noted that stability determination tests, from Marshall and Duriez methods, are both complementary and cover all the overall quality of the studied composite concretes. They only differ in two important characteristics: operating temperature of 60°C for Marshall tests against 18°C for those of Duriez in the one hand, and stress

**Table 10.** Results from Marshall tests on concretes using pure plastic bags powder as binder.

Parameter	Value
Aggregates' true volumetric density	2.69 (g/cm <sup>3</sup> )
Samples apparent hydrostatic density	2.354 (g/cm <sup>3</sup> )
True density of mixture	2.472 (g/cm <sup>3</sup> )
Bitumen volume rate	12.49 (%)
Aggregates volume rate	82.73(%)
Residual voids volume rate	4.79 (%)
Compacity rate	95.21 (%)
Aggregates volumetric density	2.225 (g/cm <sup>3</sup> )
Rate of aggregates voids	17.29 (%)
Rate of voids filled	72.37(%)
Creep flow	1.930 (x1/10 mm)
Marshall Stability	37.74 (kN)

Marshall Tests Results foil's template; Bitumen: 0%; Plastic bags powder: 100%; Binder rate/Aggregates: 5.8%.

**Table 11.** Results of Duriez tests on composite concretes bound with pure plastic bags powder.

Parameter	Value
Resistance in simple compression (1-day on the open-air at 18 °C)	94.55 (bar)
Resistance in simple compression (8-days on the air at 18 °C)	128.38 (bar)
Resistance in simple compression (1-day controlled air + 7-days water immersed at 18 °C)	94.55 (bar)
Water absorption rate (1-day/air + 7-days water immersed at 18 °C)	0.76 (%)
Coefficient of reduction	73.64 (%)
Subsidence	1.16 (-)

Duriez Tests Results foil's template; Bitumen: 0%; Plastic bags powder: pure or 100%; Binder rate/Aggregates: 5.8%.

application mode to specimen, on the other hand: along specimen generatrix in Marshall's tests against axial direction in Duriez ones.

#### **Water absorption rate of concrete bound using pure powder from plastic bags**

Concrete made of melted plastic bags powder and stored for 1-day on the controlled air and 7-days submerged in water absorbs 2.21 times less water than bituminous concrete from pure 50/70 graded bitumen and 5.26 times less than the prescribed limit on site of 4% by specifications.

#### **Marshall's creep of concrete bound using pure powder from waste plastic bags**

Marshall's creep flow is prescribed to take value between 2 and 4.10<sup>-1</sup> mm. It is known that an excess of creep flow

is especially harmful to the floor. While the bituminous concrete from pure 50/70 graded bitumen accused creep's value at the upper limit of the acceptable (3.997x10<sup>-1</sup>mm), the creep value for concrete made of plastic bags powder is located at the lower limit (1.93x10<sup>-1</sup> mm). These results allow us to affirmatively conclude that the designed concrete using pure plastic bags powder subsides two times lower than concrete made of 50/70 graded bitumen alone.

#### **Duriez subsidence of concrete bound using pure powder from waste plastic bags**

Duriez subsidence is always prescribed and must remain below or at most equal to 5%. Concrete made of melted powder from waste plastic bags collapses 4.31 times less than this requirement and 5.13 times less than the bituminous concrete from pure 50/70 graded bitumen basis (Table 11).

Ultimately, the data, collected at the end of these experi-

riments series, point out that the melted plastic bags powder, used alone, can act as a good binder for making a similar kind of bituminous concrete even though it does not have the characteristics of specific graded bitumen. Indeed, the obtained values, for some quality characteristics, such as compactness, are relatively low: 95.21 % against provided rate of 96 % to 98 % by 50/70 graded bitumen.

Despite the noticeable reduction of density for this plastic bags composite material ( $2.35 \text{ t/m}^3$ ) comparatively to that for composite material from 50/70 bitumen ( $2.42 \text{ t/m}^3$ ), it is estimated that all of the obtained other results resolutely contribute to strengthen the relevance of idea behind the massive use of waste plastic bags, as dope in the formulation and implementation of new bituminous concretes or as "pure" binder for a "similar" concretes in the context of roads construction.

However, further studies are needed to improve some of performance parameters among others quite attractive for the new formulated concretes. Prospects are promising and many fields of research are to be achieved for.

#### Quality validation for doped bituminous concretes using melted powder plastic bags

According to experienced data, the standard penetrability  $S_p$  ( $\times 1/10 \text{ mm}$ ) of a bituminous binder at temperature of  $25^\circ\text{C}$  and the Duriez stability of resulting bituminous concrete at 8-days aged on the controlled air R (bar) are linked by correlation of the following form (Duriez and Arrambide, 1959):

$$\log R + (2/3)\log S_p = \gamma = C^{\text{ste}} \quad (14)$$

More the  $\gamma$ -value approaches  $\gamma \approx 3$  (by lower values), higher is quality of the bituminous concrete. A  $\gamma$ -value of 2.875 indicates a middle quality bituminous concrete and a  $\gamma$ -value of 2.7 corresponds to frontier between the bituminous concrete and bitumen coated dense products.

In case of the proposed new binder mixes in this study, if one considers average value of recorded penetrability from the used reference 50/70 graded bitumen alone (pure that is without any added dope), being  $S_p = 61 \times 1/10 \text{ mm}$  and its Duriez stability value at 8-days aged on the controlled air:  $R = 68.67 \text{ bar}$ , one obtains  $\gamma = 3.02$  from relation (14).

It is a closed value to  $\gamma \approx 3$  which allows confirming that the developed bituminous concretes belong to the ones categorized as of very good quality.

Elsewhere, the 50/70 graded bitumen used as main bituminous binder has displayed softening point value of  $T = 36.5^\circ\text{C}$  and the derived bituminous concretes reached resistance, at 8-days conservation on the controlled air, of  $R = 68.67 \text{ bar}$ . These known values of T and R lead to determination of ratio  $1/\lambda$ , hence  $\lambda$  another quality index

that also permits categorizing the bituminous concretes and is calculated from the following relation:

$$1/\lambda = (T)^{2.64} / R \quad (15)$$

In replacing T and R by their respective values, one arrives to  $1/\lambda$ :

$$1/\lambda = (36.5)^{2.64} / (68.67) = 194$$

This value of  $\lambda = 1/194$  is largely higher than limit of  $\lambda = 1/500$  marking the good quality bituminous concretes compared to those designated as middle-quality ones having  $\lambda$ -value of  $1/750$  on one hand and to concretes situated at frontier between the said bituminous and bitumen dense coated products possessing  $\lambda$ -value of  $1/1000$ , on the other.

The thermal susceptibility (h) of grading bitumen is another important quality indicator in terms of so called "maintain and durability" for a bituminous concrete, as does adhesivity for a bituminous binder. It's linked to usually employed Penetration Index (IP) determined by following equation (Naskara and Chakia, 2010; Jeuffroy, 1978):

$$h = [\log 800 - \log P_{25}] / [T_{\text{BA}} - 25] = (1/50) \cdot [20 - \text{IP}] / [10 + \text{IP}] \quad (16)$$

With  $T_{\text{BA}}$  as the Ball and Ring temperature in measurements of binder (bitumen) penetrability.

The value of penetrability index for any grading bitumen at temperature of  $25^\circ\text{C}$  ( $P_{25}$ ) is approximately equal to 800. More IP-value is high, minus this bitumen's thermally susceptible. Current values of IP are comprised between -3 and +8 while simple distillation bitumens have negative index values or lesser than 1 and blowing bitumens, feebly or less heat susceptible, disclosed positive indexes. Application of relation (16) and those established limits let concluding that:

1) The thermal susceptibility of pure 50/70 graded bitumen is higher ( $\text{IP} = -5$ ). This might explain some of these frequently recorded defaults, provoked by the combined effects of traffic and operating temperature on the Beninese coated roads, using this kind of graded bitumen. From then, it must be adequate for hot climate countries, like Benin Republic and those of sub-region, where the problem to solve concerns temperature always higher ( $27$  to  $45^\circ\text{C}$ ) than the chosen reference of  $25^\circ\text{C}$  in temperate climate countries, to search for lower convenient thermal susceptibility in displacing IP-values towards zero, seeing positive values.

2) The doped bitumens, using from 2% to 12% (wt/wt.mix) of powder from the melted waste plastic bags, enter the classical susceptibility values laying in IP-interval going from  $\text{IP} = -3$  to  $\text{IP} = -2$ . The incorporation of melted powder of waste plastic bags positively acts in

that, it permits displacing the penetrability index from that of pure 50/70 graded bitumen (IP=-5) towards IP-interval of [-3, -2] in a subsequent increase tendency, even though, the resulting values are negative but well located the corresponding binders into those possessing IP-values in interval of [-3, +8] previously located above.

3) At 15% powder content (wt/wt.mix) of melted waste plastic bags, if glycerol reached temperature of 110°C was considered as softening point, the derived value for thermal susceptibility index might be of 6. In this case, corresponding doped bitumen mix would be the best, compared with others, in the operating conditions of the coated roads of Benin.

## Conclusions

The goal in this investigation is to identify the relevant and promising means to recycle the waste plastic bags that offer spectacular nuisance in all cities and villages of Benin Republic and of the sub-region. The construction processes were identified as being the potential reducers and then, in significant manner, of the huge amount of harmful waste plastic bags. To do this, the chosen, developed and analyzed process, in this article, was the one oriented towards utilization of the waste plastic bags (thermally melted, cooled and reduced into powder), as a dope for bituminous binders in roads construction. The study identified and analyzed the essential characteristics of the developed bituminous binders by partially or completely substituting the obtained melted from heated waste plastic bags, finely ground in powder (0.160 mm mean diameter) to the 50/70 graded bitumen. At the end of testing series based on ten (10) variants of doped bitumens mixes with powder from the melted waste plastic bags at respective percentages of 0, 2, 4, 6, 8, 10, 12, 15, 18 and 20% (wt/wt.mix), the reached results allowed concluding that the realized substitution has had the effects of progressively declassifying the bituminous binders towards the hardest grading bitumens: from 50/70, transiting by 40/60, 35/50, 30/45 to even 20/30. These different bituminous binder mixes, obtained from the incorporation of powder from the melted waste plastic bags have developed a better adhesivity to aggregates in corresponding built bituminous concretes. They showed increasing values of Duriez stability of 14.28 - 29.04 % with respect to the used main binder as control consisting of 50/70 graded bitumen alone, when increasing the rate of waste plastic bags powder. It resulted in a weak decreasing trend for the bituminous concretes bulk density: -0.99%.

The decrease tendency was relatively significant, as predicted from creep's measurement which has dropped from 3.997 to 2.687% (being a reduction of 32.77%), leading then to suitable value for a good coating. Finally, the results of this study revealed also that, the powder from the melted waste plastic bags, although it does not have identical characteristics to conventional 50/70 graded

bitumen, is able, in itself used alone, to act as a binder of good quality in the manufacture of similar concretes as that from studied 50/70 bitumen. Further studies are therefore needed in intend for finely improving some features of its binder characteristics. However, results of the performed tests on the built bituminous concrete specimens from pure powder of melted waste plastic bags showed that, Marshall' stability on the one hand, and Duriez stability at 8 days on controlled air, from each other, are significantly higher, by approximately 80 and 87% respectively, than that provided by 50/70 graded bitumen. The results from thermal susceptibility study let clearly knowing the consequence of incorporating powder from melted waste plastic bags, improving bituminous binder's penetrability index intimately linked with the consistency (seeing adhesivity) and then durability of bituminous concretes used in road coatings or pavements.

## Conflict of Interests

The author(s) have not declared any conflict of interests.

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*Full Length Research Paper*

## Empirical modeling of solar radiation for selected cities in Nigeria using multivariate regression technique

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In this paper, the data for solar radiation, minimum and maximum temperatures, wind speed and evaporation for the years 1970-1995 and for fourteen stations taken over Nigeria were obtained from the archives of the Nigerian Meteorological Agency (NIMET), Oshodi, Lagos. The distributions of solar radiation with each of the four meteorological variables were observed. It was found that solar radiation was adequately monitored by each of the variables indicating that the linear combination of the variables could be used to developed model from where solar radiation can be evaluated. Consequently, a multivariate linear regression model was developed for each of the stations. The statistical indicators such as  $R^2$ , MBE, RMSE and MPE were calculated to estimate the efficiency of the developed models. For instance, the values of the  $R^2$ , MBE, RMSE and MPE calculated for Sokoto, a Sahelian station are 0.5349, 0.0273, 0.4154 and 0.0811, respectively, which show that the model for Sokoto is significant. Those for other stations have also been calculated with all showing high level of signicance at 0.05 alpha level.

**Key words:** Solar radiation, meteorological variables, correlation coefficient, multivariate regression, evaporation, significance.

### INTRODUCTION

Solar radiation received at the earth's surface is essential for the development and utilization of solar energy devices. It is needed for designing collectors for solar heaters and other photovoltaic equipment that depend on solar energy. Incoming solar radiation has a significant role in hydrological and crop growth modelling. For instance, it is a key input for estimating potential evapotranspiration which play a major role in the design of water supply storage reservoirs and irrigation systems (Sanusi and Abisoye, 2011). The solar radiation reaching the earth's surface depends on the climatic

condition of the specific location, and this is essential for accurate prediction and design of a solar energy system (Burari and Sambo, 2001). Technology for measuring solar radiation is costly and has instrumental hazards (Alam et al., 2005); this has led to paucity of it in many stations in the developing countries (including Nigeria). Thus, alternative methods for estimating these data are required (Al-Salihi et al., 2010). One of these methods is the use of empirical models. Accurate empirical modelling depends on the quality and quantity of the measured data used in developing it, and is a good

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**Figure 1.** A map of Nigeria showing four climatic regions and the studied stations.

tool for generating solar radiation of any kind (whether global, direct or diffuse) at locations where measured data are not available.

When solar radiation enters the Earth atmosphere, a part of the incident energy is removed through the processes of scattering, absorption and reflection. The scattering of solar radiation is mainly by atmospheric molecules and aerosols while the absorption of solar radiation is by stratospheric ozone, water vapor, oxygen, carbon (IV) oxide, as well as clouds. The reflection of solar radiation on the other hand, is mainly by clouds and this plays an overriding part in reducing the energy density of the solar radiation reaching the surface of the Earth (Exell, 2000).

Several models have been proposed to estimate global solar radiation. Angstrom (1924) was the first scientist known to suggest a simple linear relationship to estimate global solar radiation. Badescu (Badescu, 1999) studied existing relationships between monthly mean clearness index and the number of bright sunshine hours using the data obtained from Romania. Trabea and Shaltout (2000) studied the correlation between the measurements of global solar radiation and the meteorological parameters using solar radiation, mean daily maximum temperature, mean daily relative humidity, mean daily sea level pressure, mean daily

vapour pressure and hours of bright sunshine data obtained from different parts of Egypt; while Sfetsos and Coonock (2000) used artificial intelligence techniques to forecast hourly global solar radiation. Okogbue and Adedokun (2002) estimated the global solar radiation at Ondo, Nigeria.

The main objective of the present study is to develop predictive models, using multi-variate regression analysis technique to predict solar radiation using four meteorological parameters, that is, minimum and maximum temperature, wind speed and evaporation for the study area and other locations having similar climatic characteristics in Nigeria. This will be useful in the development and the applications of solar energy technology.

## METHODOLOGY

The monthly mean solar radiation, minimum and maximum temperatures, wind speed and evaporation data were obtained from the Archives of Nigerian Meteorological Agency, Oshodi, Lagos. The data obtained covered a period of twenty-six years (1970-1995). The stations were grouped according to their respective weather condition as shown in Figure 1. The distributions of the solar radiation with each of the atmospheric parameters were observed. It should be noted here that the solar radiation data were measured using Gun-Bellani distillate. Measurements were taken in millilitres (ml) which were converted to useful format



(MJ/m<sup>2</sup>) using a conversion factor proposed by Folayan (Folayan, 1988), which is 1 ml = 1.357 MJ/m<sup>2</sup>

### Relevant multivariate linear regression analysis theory

Multivariate regression analysis is a technique for modeling and analyzing several variables when the focus is on the relationship between a dependent variable and one or more independent variables. For instance, let  $z_1, z_2, \dots, z_r$  be a set of  $r$  predictors believed to be related to a response variable  $Y$ . The multivariate linear regression model for the  $j$ th sample unit has the form:

$$Y = \alpha + \beta_1 z_{j1} + \beta_2 z_{j2} + \dots + \beta_r z_{jr} + \varepsilon_j \quad 1$$

where  $\varepsilon_j$  is a random error, the  $\beta_i$  where  $i = 1, 2, \dots, r$  are unknown parameter estimates and  $\alpha$  is the intercept. With  $n$  independent observations, one model can be written for each sample unit or can be organized into vectors and matrices so that the model now becomes

$$Y = Z\beta + \varepsilon \quad 2$$

where

$$Y = \begin{pmatrix} y_1 \\ y_2 \\ \vdots \\ y_n \end{pmatrix}, \quad Z = \begin{pmatrix} z_{j1} \\ z_{j2} \\ \vdots \\ z_{jn} \end{pmatrix} = \begin{pmatrix} z_{11} & \dots & z_{1r} \\ z_{21} & \dots & z_{2r} \\ \vdots & \dots & \vdots \\ z_{n1} & \dots & z_{nr} \end{pmatrix}, \quad \beta = \begin{pmatrix} \beta_1 \\ \beta_2 \\ \vdots \\ \beta_r \end{pmatrix}, \quad \varepsilon = \begin{pmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \vdots \\ \varepsilon_n \end{pmatrix} \quad 3$$

### Least squares estimation

Ordinary least squares (OLS) estimates are commonly used to analyze both experimental and observational data. The OLS method minimizes the sum of squared residual, and leads to a closed-form expression for the estimated value of the unknown parameter  $\beta$ :

$$\hat{\beta} = (Z'Z)^{-1} Z'Y = \left( \frac{1}{n} \sum z_j z_j' \right)^{-1} \left( \frac{1}{n} \sum z_j y_j \right) \quad 4$$

where  $\hat{\beta}$  denote the least squares estimate of  $\beta$  and  $Z'$  denotes the transpose of  $Z$ .

## RESULTS AND DISCUSSION

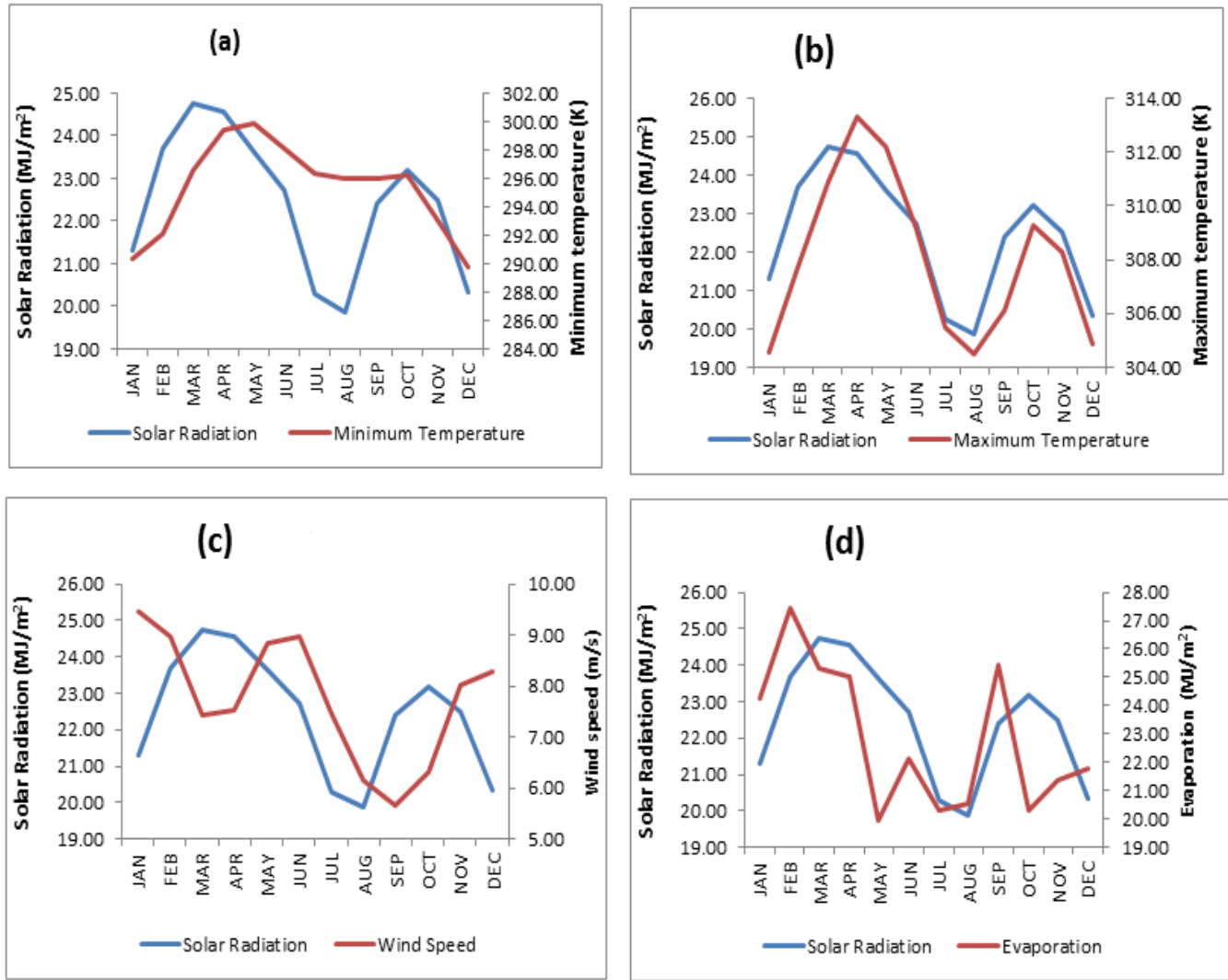
### Distribution of solar radiation with meteorological variables

Figures 2 to 5 show the distribution of solar radiation with meteorological variables, which are, the minimum and maximum temperatures, wind speed and evaporation for four stations, that is one from each of the four climatic regions in Nigeria.

In Sokoto, it was observed that minimum and maximum temperatures and evaporation increased with solar radiation between January and June and also between September and November. A downward trend was discernible

between July-September as shown in Figures 2a-b. The increasing trends between January and June may be due to the fact that during these months, dry season condition is predominant in this station. The decreasing trend in July-September may be due to the presence of disturbances like cumulous cloud and cloud cluster which are significant enough to cause variation in weather (Adeyemi, 2004). During this period, all regions in Nigeria will be experiencing intense rainfall because the intertropical discontinuity (ITD) would have reached its maximum northern position. Wind speed on other hand shows an opposite trend to solar radiation during dry season. For instance, between January and March, solar radiation increases as wind speed decreases. However, wind speed and solar radiation show the same downward trend between June and August, the rainy season in the Sahelian zone (Figure 2c). This shows that intense rainfall decreases the intensity of solar radiation and the rate of wind flow in the zone. Meanwhile, there is increasing trends between September and November, another phase of dry season. This may due to the fact that the dry season period in the zone is characterized by mostly turbulent flow of wind. Solar radiation and evaporation show the same increasing and downward trends (Figure 2d). The increasing trends are discernible between January-May and September-November, the dry season period and downward trends between June and August, the rainy season period. This is in agreement with Graham et al. (2004) argument that the physics of evaporation shows that the evaporative demand of the atmosphere is directly dependent on the net radiation which is dependent on solar radiation.

In Yola, there are increasing trends in variations of solar radiation with temperatures, wind speed and evaporation between January-April and September-December, the dry season period (Figures 3a-d). This may due to the topography of the zone that is characterized by short grasses and scattered drought-resistant tree which aids incessant surface heating that caused water vapour to be transported to the higher layers of the atmosphere through buoyancy (Adeyemi et al., 2004; Aro, 1975). Also, solar radiation shows downward trends with the four meteorological variables between April and August, the rainy season period in the zone. This may likened to the presence of the localized convection due to the usual long period of humid condition in the zone. In Ibadan, the dry and the wet season occurrence are greatly influenced by its latitudinal location and solar radiation has considerable seasonal variations. There are downward trends between March and September in the distribution of solar radiation with temperatures and evaporation as shown in Figures 4a, b and d, that is, during the rainy season period. This may due to the fact that these months being the core rainy months, are characterized by incessant cloud formation and thereby depleting the amount of solar radiation reaching the

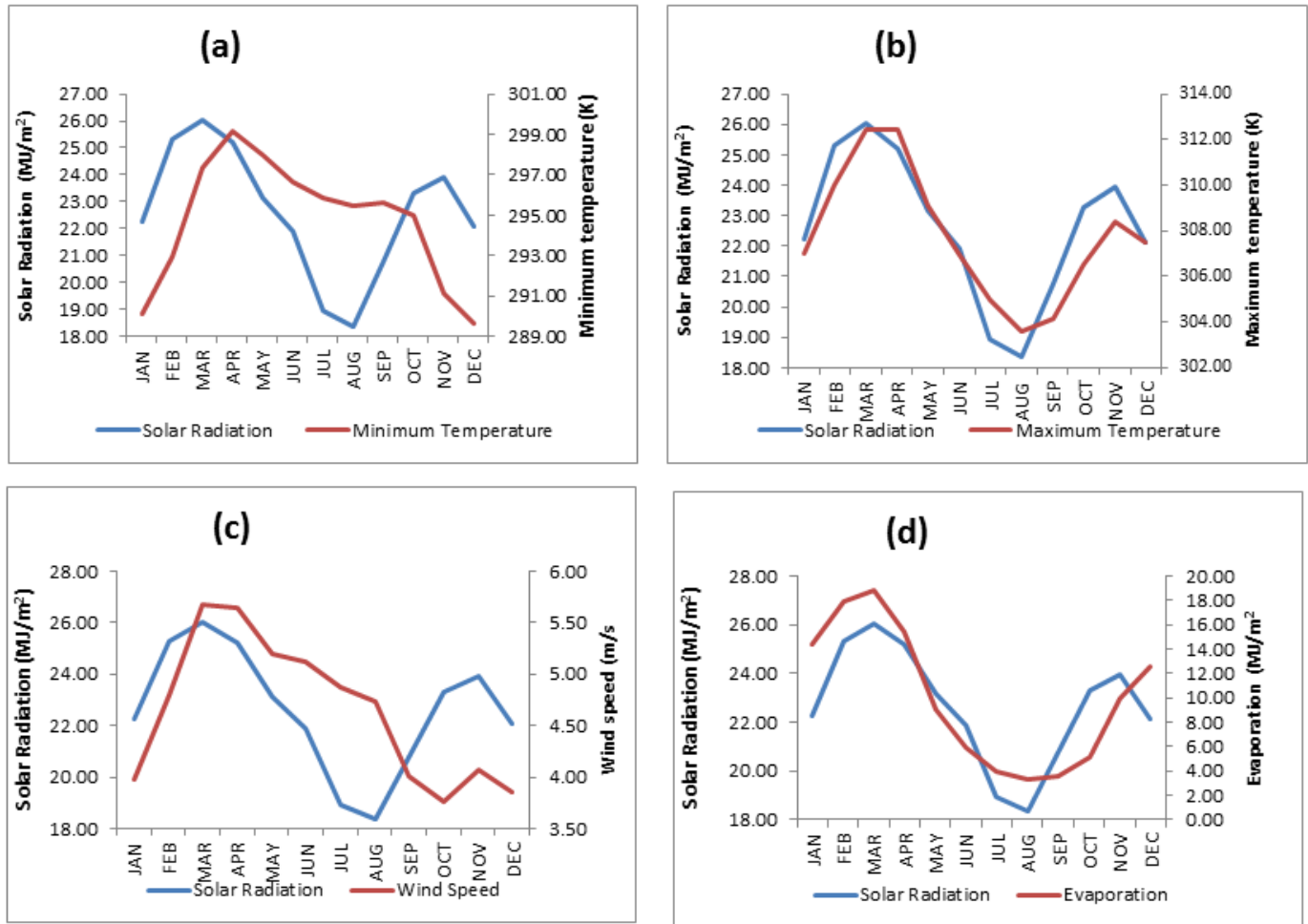


**Figure 2.** Distribution of (a) solar radiation and minimum temperature (b) solar radiation and maximum temperature (c) solar radiation and wind speed (d) solar radiation and evaporation at Sokoto.

Earth's surface (Ajayi and Adeyemi, 2009). The increasing trends are observed between October and March. This may be due to the prevalence of the dry CT air which characterizes the dry season. The period is characterized by low humidity and high rate of evaporation aided by the increase in solar radiation and in air temperature in the zone. On the other hand, there is a downward trend in the distribution of solar radiation with wind speed between June and August (Figure 4c). This may be due to the fact that the zone is under the influence of moist maritime south-western monsoon wind which blows inland from the Atlantic Ocean. The dry season occurs from November to February during which the dry dust laden winds blow from the Sahara desert. This period is characterized by low humidity and high rate of evaporation (Ajayi and Adeyemi, 2009). There is a general decreasing trend in solar radiation between

November and January in Sokoto, Yola and Ibadan respectively (Figure 2 to 4a-d). These are expected because November and January are harmattan months when aerosol mass loading greatly reduces the intensity of solar radiation (Babatunde and Aro, 2000).

In Port-Harcourt, solar radiation has two peak values in February and November (Figures 5a-d). This is expected because of a very high sunshine hour which is obtainable in these months due to high cleanness index (Aro, 1975). Least solar radiation is observed in the months of July and August, respectively. This is expected because heavy rainfall characterizes these months in the station. Therefore, the total solar radiation recorded is quite low because of the wet atmosphere and the presence of heavy clouds. If the weather is cloudy, the solar radiation value would be largely affected.



**Figure 3.** Distribution of (a) solar radiation and minimum temperature (b) solar radiation and maximum temperature (c) solar radiation and wind speed (d) solar radiation and evaporation at Yola.

This is because the solar radiation at normal incidence received at the surface of the earth is subjected to variations due to change in the extraterrestrial radiation and also the two significant phenomena which are the atmospheric scattering by air molecules, water and dust and the atmospheric absorption by  $O_2$ ,  $H_2O$ ,  $CO_2$  (Lam et al., 2002). Wind speed increases with solar radiation between November and February while it shows downward trends between March and August in the station as shown in Figure 5c. This may be due to excessive rainfall in these months in the zone.

### Model development

The multivariate linear regression (MLR) modeling technique was then applied and a model of the form as shown in Equation 6 was developed for all stations using 1970-1990 data.

$$H = \alpha + \beta_1 T_{min} + \beta_2 T_{max} + \beta_3 W_s + \beta_4 E_p + \epsilon \quad 5$$

where  $\alpha$  is the regression constant,  $\epsilon$  is the error term,  $\beta_1$ ,  $\beta_2$ ,  $\beta_3$ , and  $\beta_4$  are parameter estimates of minimum temperature ( $T_{min}$ ), maximum temperature ( $T_{max}$ ), evaporation ( $E_p$ ) and wind speed ( $W_s$ ) respectively for each of the stations.

The parameter estimates for the empirical model for evaluating solar radiation for each of the fourteen stations are shown in the Table 1. For instance, Sokoto on Lat.  $13.5^\circ$ , Long.  $5.25^\circ$  model is:

$$H = -83.783 - 0.184T_{min} + 0.526T_{max} - 0.064W_s + 0.079E_p \quad (6)$$

### Model testing and assessment

The models were then validated using surface data of 1991-1995 for all the parameters. The performance of the developed models was tested with coefficient of determination ( $R^2$ ), root mean square error (RMSE)

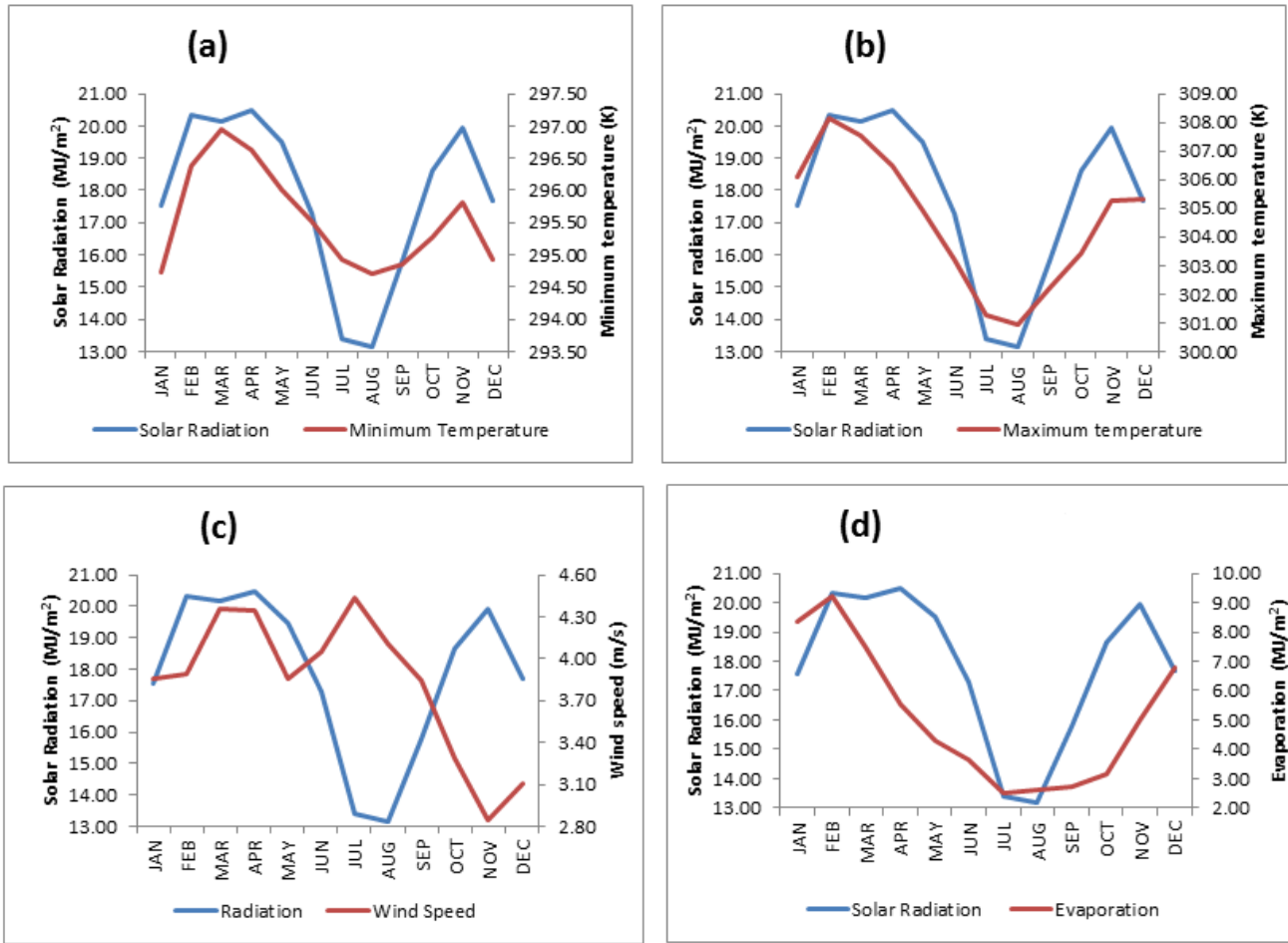


Figure 4. Distribution of (a) solar radiation and minimum temperature (b) solar radiation and maximum temperature (c) solar radiation and wind speed (d) solar radiation and evaporation at Ibadan.

and mean bias error (MBE), mean percentage error (MPE) and their values are shown in Table 2.

The expressions for evaluating the value of MBE, RMSE and MPE as stated by Okundamiya and Nzeako (2010) are shown in Equations (8-10):

$$MBE = \frac{1}{N} \sum_{n=1}^n (H_p - H_a) \tag{7}$$

$$RMSE = \sqrt{\frac{1}{N} \left[ \sum_{n=1}^n (H_p - H_a)^2 \right]} \tag{8}$$

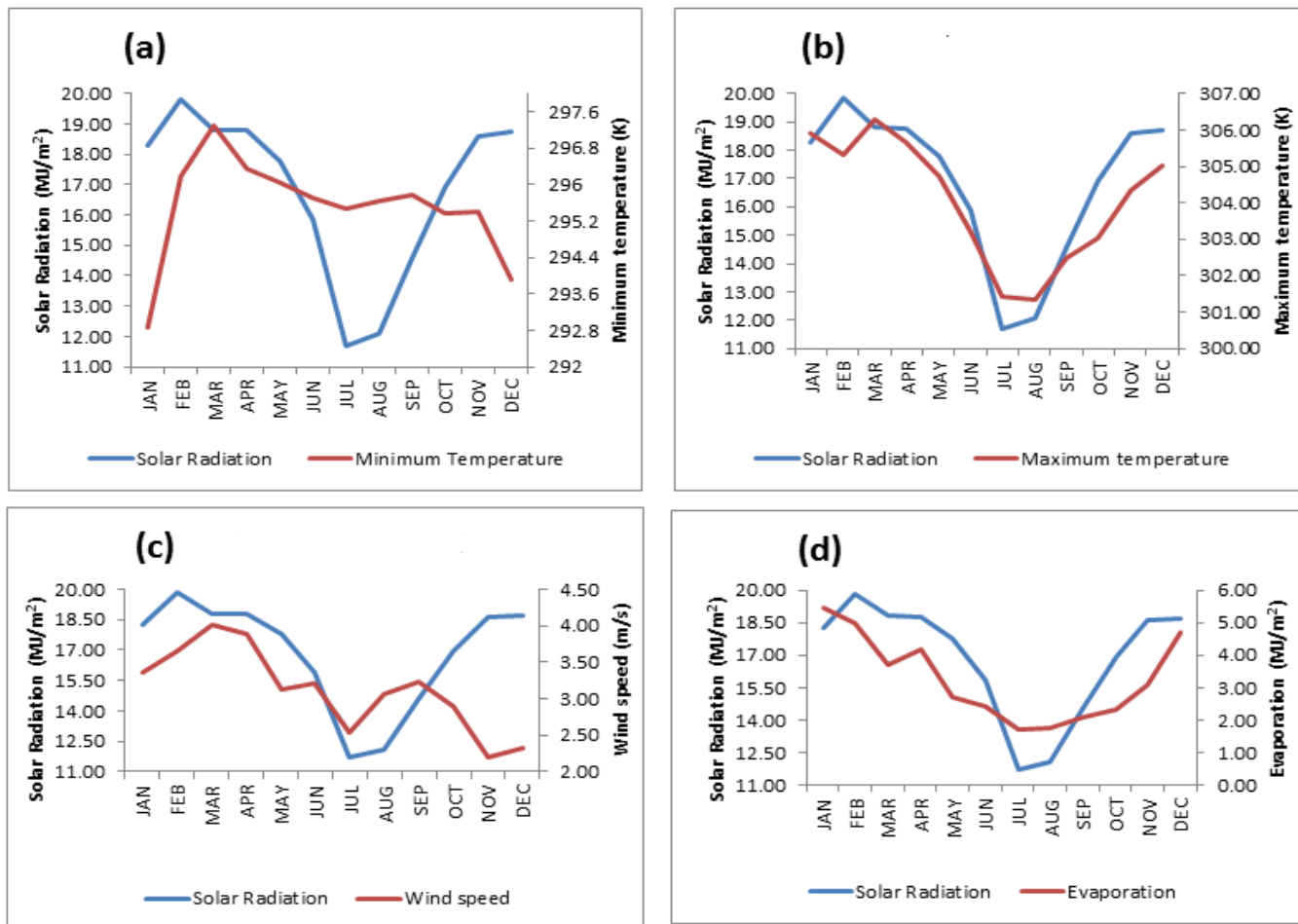
$$MPE = \frac{1}{N} \sum_{n=1}^n \left[ \frac{H_a - H_p}{H_a} \times 100 \right] \tag{9}$$

$$t-test = \sqrt{\frac{(P-1)(MBE)^2}{(RMSE)^2 - (MBE)^2}} \tag{10}$$

where  $H_p$  and  $H_m$  is the predicted and measured values of solar radiation and  $N$  is the total number of observations. These indicators are mainly employed for

adjustment of solar radiation data (Halouani and Nguyen,1993; Falayi and Rabi, 2005; Okogbue and Adedokun, 2002; Al-Salihi et al., 2010). The models developed were applied to evaluate solar radiation at the stations. The result of these was compared with the actual values obtained for all stations which are the average as shown in Table 2. The agreements are remarkable.

From Table 2, the values of the coefficient of determination ( $R^2$ ) which show the proportion of variance accounted for by the correlation measured values with predicted values and the significance of the developed models to predict the solar radiation vary from 0.3017-0.7655 for the selected stations. The graphical demonstration of the correlation of measured and predicted values are shown in Figures 6 to 8. There are good agreement between the predicted values obtained from the models and the actual measured values of the surface data of solar radiation. The values of the mean bias error (MBE) indicate the average deviation of the predicted values from the actual measured values.



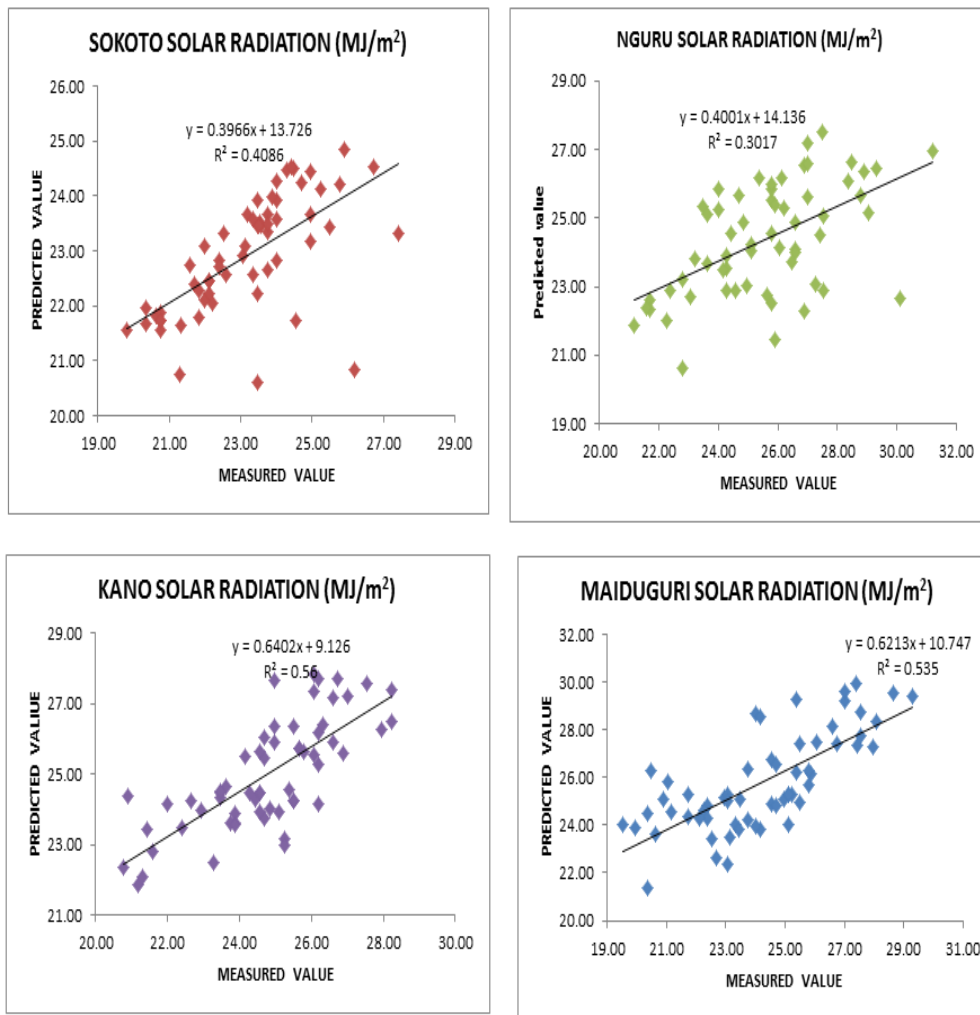
**Figure 5.** Distribution of (a) solar radiation and minimum temperature (b) solar radiation and maximum temperature (c) solar radiation and wind speed (d) solar radiation and evaporation at Port-Harcourt.

**Table 1.** Multivariate parameter estimates of the models for the studies stations.

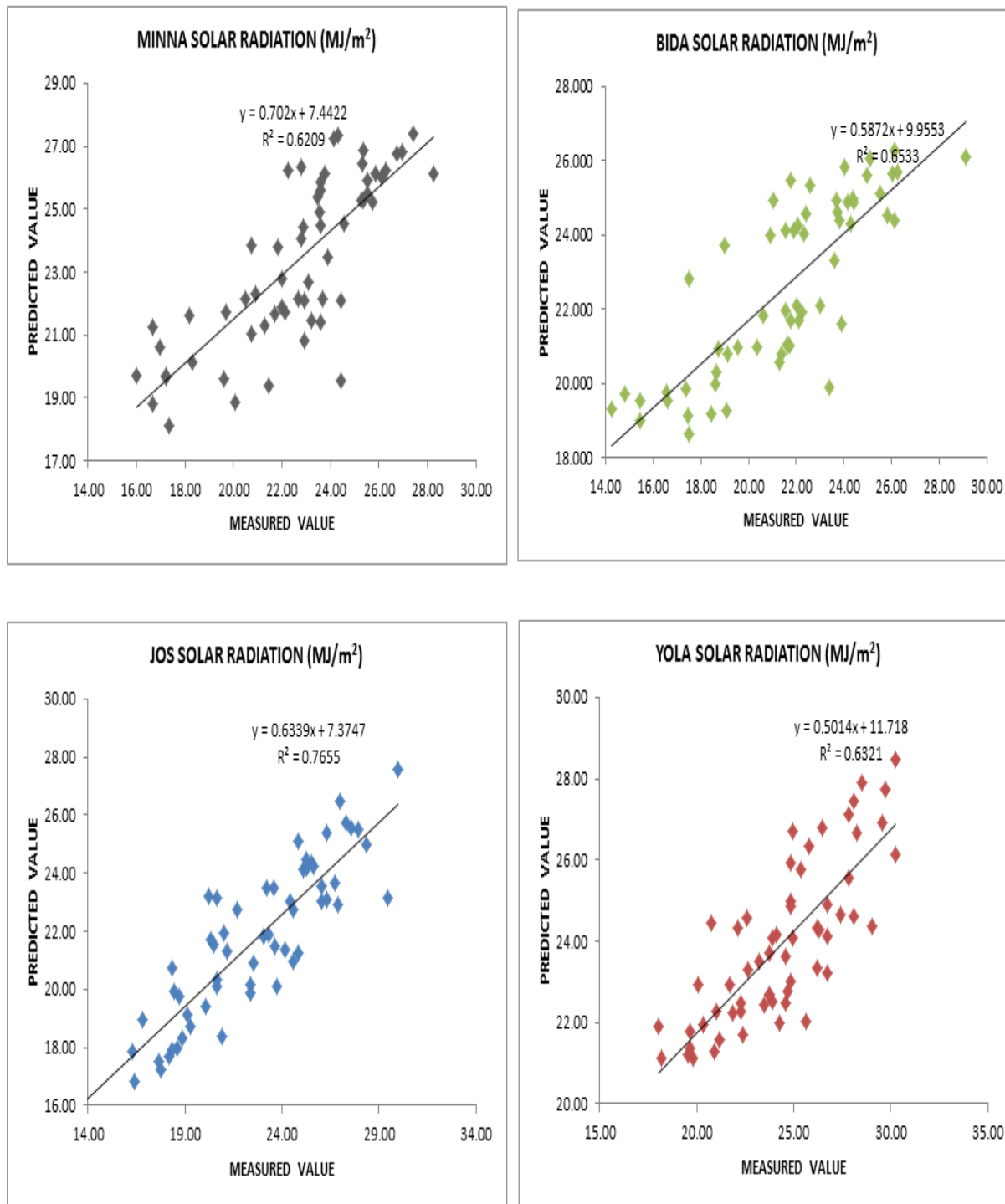
Station	Location		Models' parameters estimates					
	Lat (°N )	Lon (°E)	$\alpha$	$\beta_1$	$\beta_2$	$\beta_3$	$\beta_4$	p-value
Sokoto	13	5.25	-83.7827	-0.1837	0.5256	0.0642	-0.0797	0.0000
Kano	12.07	8.43	-120.731	0.0149	0.4593	0.0863	-0.0196	0.0000
Nguru	12.91	5.30	-99.1411	-0.1119	0.5013	0.4478	0.0358	0.0000
Maiduguri	11.91	13.17	-51.7748	0.4025	-0.1448	-0.3399	0.3799	0.0000
Minna	9.62	6.53	-204.529	-0.4197	1.1483	0.2715	-0.21688	0.0000
Jos	9.87	8.52	-192.513	-0.2533	0.9523	0.0370	0.08928	0.0000
Bida	9.08	6.02	-165.524	-0.3573	0.9558	0.3479	-0.06878	0.0000
Yola	9.23	12.47	-148.911	0.0379	0.5248	-0.4690	0.099828	0.0000
Osogbo	7.73	4.48	-225.887	-0.3327	1.1239	0.4135	-0.0383	0.0000
Ibadan	7.43	3.9	-208.052	-0.5119	1.2417	0.1476	-0.0944	0.0000
Ikeja	6.58	3.33	-227.319	-0.4350	1.2284	0.3887	-0.0968	0.0000
PH	4.85	7.02	-212.561	-0.3019	1.0498	0.3169	0.0216	0.0000
Benin	6.32	5.6	-205.085	-0.5191	1.2330	0.4416	-0.0476	0.0000
Enugu	6.37	7.55	-216.977	-0.4366	1.2001	0.0569	-0.0753	0.0000

**Table 2.** Application of the multivariate proposed model for each of the fourteen stations using 1991-1995 data.

Station	Solar radiation		Performance estimates			
	Measured	Predicted	R <sup>2</sup>	MBE	RMSE	MPE
Sokoto	23.20	22.93	0.4086	-0.2717	1.3186	0.8668
Kano	24.74	24.96	0.5600	0.2248	1.2282	-1.1148
Nguru	25.98	24.37	0.3017	-1.2092	2.2361	4.3238
Maiduguri	24.20	25.78	0.5350	1.5808	2.2751	-6.4854
Minna	22.59	23.30	0.6209	0.7120	1.9751	-3.8081
Jos	22.63	21.72	0.7655	-1.9094	2.0708	3.0847
Yola	24.35	23.30	0.6321	-0.4261	1.9346	0.9346
Bida	21.51	22.59	0.6533	1.0763	2.1929	-6.1701
Ibadan	18.12	19.26	0.7132	1.1458	1.9122	-7.2537
Osogbo	17.77	19.15	0.4148	1.3834	2.5899	-9.5505
Enugu	17.03	19.30	0.6604	2.6714	3.1111	-17.150
Benin	15.92	18.45	0.5409	2.6234	3.0702	-17.265
Ikeja	15.19	18.45	0.3225	-2.6345	3.4697	-18.682
Port-Harcourt	16.75	18.98	0.5314	2.2307	3.0028	-15.489



**Figure 6.** The correlation between the predicted and measured values of the monthly solar radiation Sokoto, Kano, Maiduguri and Nguru Stations in Nigeria.

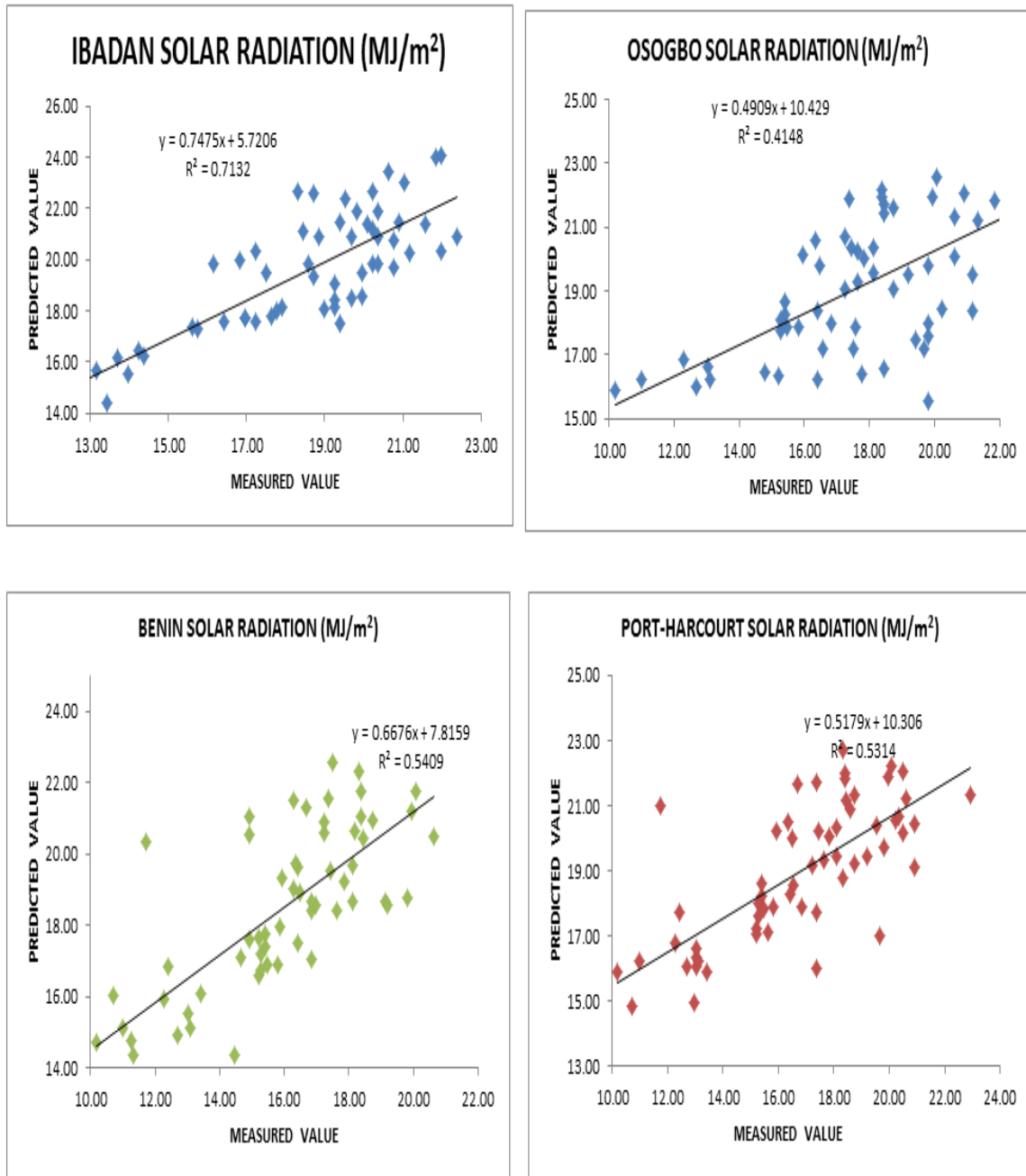


**Figure 7.** The correlation between the predicted and measured values of the monthly solar radiation for Bida, Minna, Jos and Yola Stations in Nigeria.

The MBE values vary from negative values to the positive values (lowest for Ikeja and highest for Benin). The low values of MBE generally show that the developed models are significant for predicting solar radiations. The MBE

values are suitable for the models for each of the fourteen stations (Okundamiya and Nzeako, 2010).

The root mean square error (RMSE) values indicate a measure of the variation of predicted values from the



**Figure 8.** The correlation between the predicted and measured values of the monthly solar radiation for Osogbo, Ibadan, Port-Harcourt and Benin Stations in Nigeria

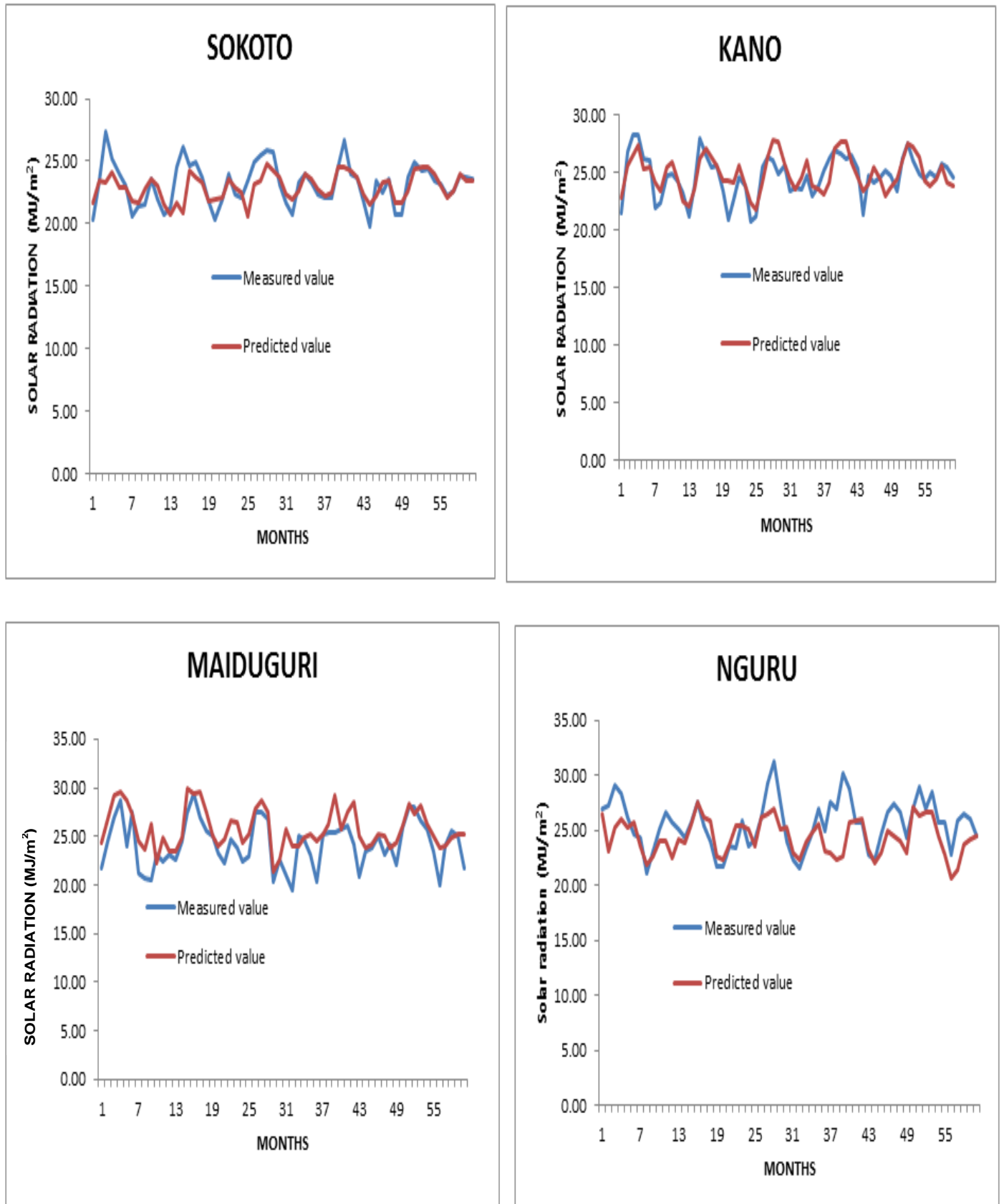
actual measured values. The RMSE values vary from negative values to the positive values (lowest for Kano and highest for Ikeja). The MPE values are suitable for the models for each of the fourteen stations. Therefore, all the developed models give long term performance (Babatunde and Aro, 2000). The RMSE values are suitable for the models for each of the fourteen stations. Therefore, term by term comparison is allowed for all the developed models (Sanusi and Abisoye, 2011).

The values of mean percentage error MPE give long term performance of the developed models. They also

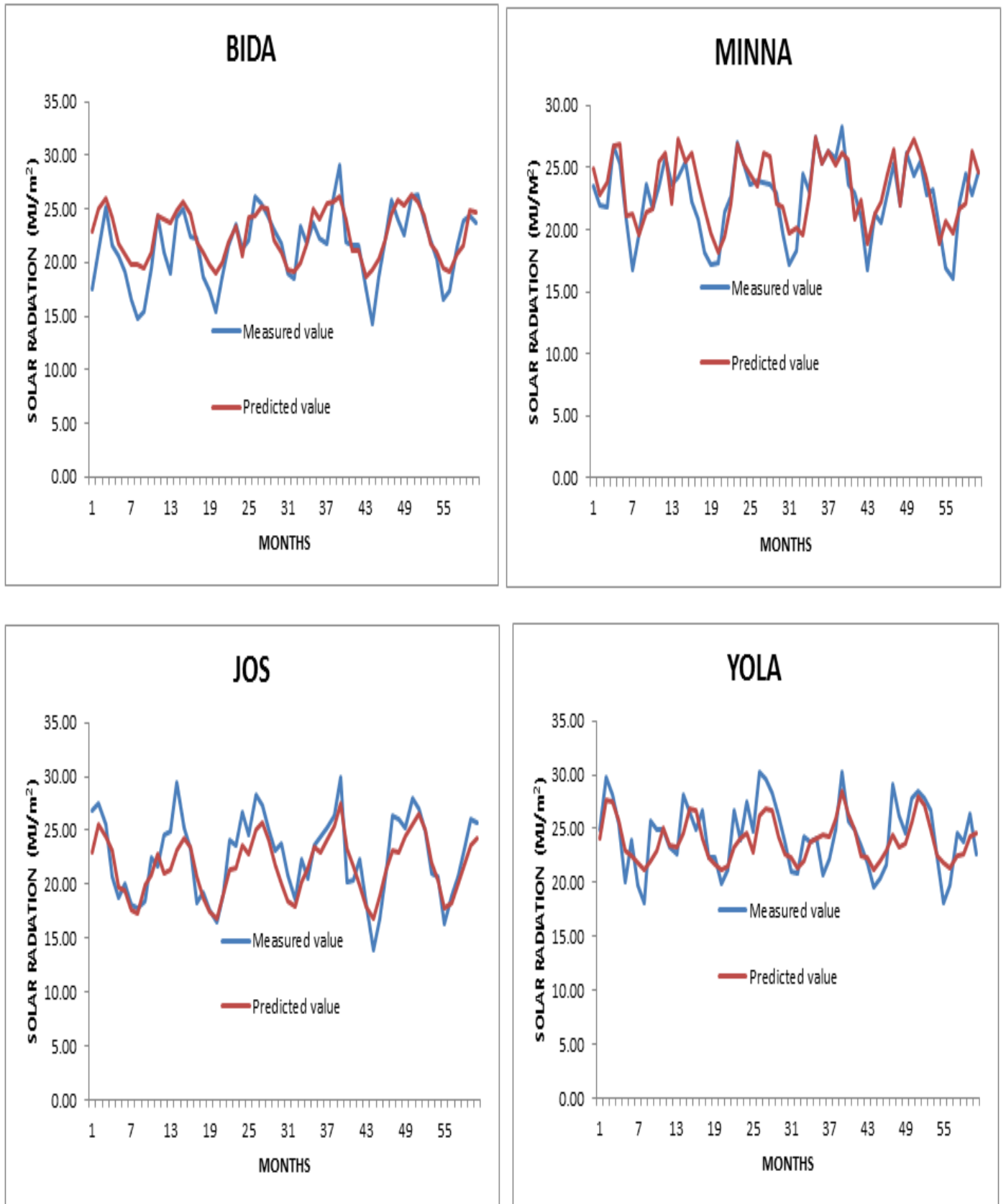
vary from negative values to the positive values (lowest for Ikeja and highest for Nguru). The MPE values are suitable for the models for each of the fourteen stations. Therefore, all the developed models give long term performance (Babatunde and Aro, 2000).

Added to these, the graph of variations plotted for the measured solar radiation for each of the four climatic regions along with their predicted values showed that solar radiation was well monitored at all the regions by the models (Figures 9 to 11).

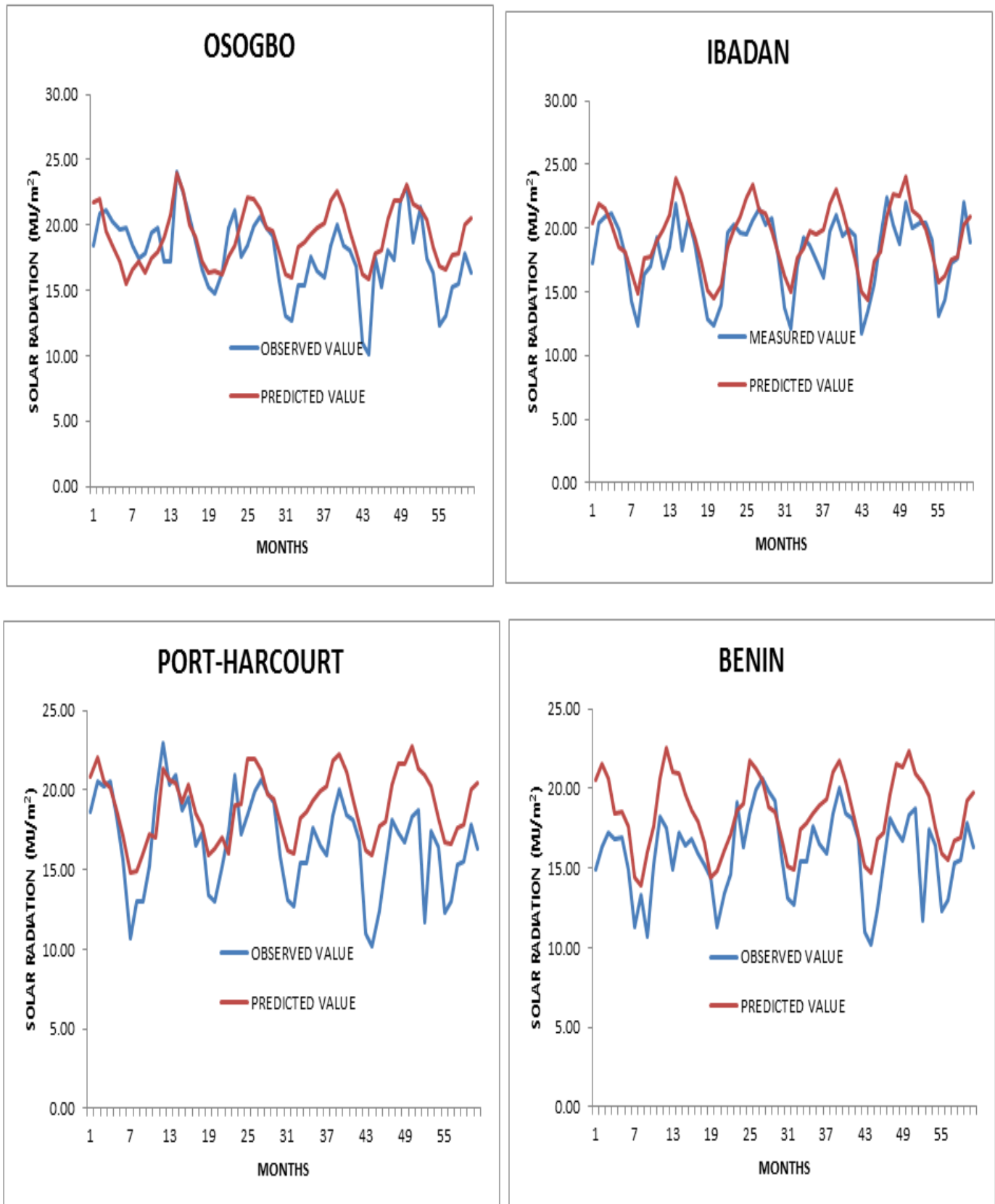




**Figure 9.** The variations of the predicted and measured values of the monthly solar radiation for Sokoto, Kano, Maiduguri and Nguru stations in Nigeria.



**Figure 10.** The variations of the predicted and measured values of the monthly solar radiation for Bida, Minna, Jos and Yola stations in Nigeria.



**Figure 11.** The variations of the predicted and measured values of the monthly solar radiation for Osogbo, Ibadan, Port-Harcourt and Benin Stations in Nigeria.

## Conclusion

The distribution of solar radiation with meteorological variables for fourteen stations which represent climatic conditions in Nigeria shows that the linear combination of these variables can be used to predict solar radiation. Analysis have shown that strong correlation exists between solar radiation and all the meteorological parameters at the selected stations. The statistical indicators have also confirmed the efficiency of the developed models. For instance, the values of  $R^2$ , MBE, RMSE and MPE for Sokoto, a Sahelian station are 0.5349,-0.0273,0.4154 and 0.0811 respectively, showing that the model for Sokoto is significant. Those for other stations have also been calculated with all showing high level of significance at 0.05 alpha levels. Therefore, the multivariate linear models developed in this research work for each of the fourteen stations is suitable for estimating solar radiation data in the stations and their proximate cities.

## Conflict of Interests

The author(s) have not declared any conflict of interests.

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Full Length Research Paper

## Variation of small scale wetland fishery in relation to land use within Mpologoma riverine marsh in Eastern Uganda

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In densely populated areas such as those in Eastern Uganda where livelihoods demands create immense pressure on environmental resources, small scale wetland fisheries may be disturbed by agriculture practices. The study carried out between 2011 and 2012, investigated the variation of fish catch at the different wetland sites in relation to land use in Mpologoma riverine marsh. Four sites were identified to represent different land uses; intact wetland, minimally disturbed, highly disturbed with small scale farmers and one with a large scale irrigation scheme. Data was collected on water quality, wetland fish species catch and catch per unit effort from the different sites. Conductivity and dissolved oxygen levels significantly differed between sites and explained 72.03% of the variance among sites. Seven fish taxa dominated the wetland fishery. Large sized fish species catch, *Clarias gariepinus* and *Protopterus aethiopicus* (range of 0.45 to 38 and 0.25 to 20 kg/day, respectively) was higher at the less disturbed sites than at highly disturbed sites which accounted for over 91.5% of total wetland catch. *Tilapia zillii* and *Oreochomis leucostictus* catch were also higher at the less disturbed sites while the small fish species (*Haplochomis* sp, *Clarias liocephalus* and *C. alluaudi*) did not vary with site. Conductivity and dissolved oxygen significantly correlated with the two large fish species' catch but did not correlate with small fish species catch. Agricultural activities in the wetland negatively affected the life history strategies of large fish species, leading to low catch rates at the highly disturbed site. Therefore, there is need to control land use changes to secure high productivity of small scale fisheries in the riverine wetland.

**Key words:** Papyrus wetland, fish, catch, water quality, disturbance.

### INTRODUCTION

Small-scale fisheries play a significant role in human and socio-economic development and they are an entry point for poverty reduction though their role in generating revenues and creating employment, and their contribution

to food security (Heck et al., 2007; Bene et al., 2010). These are wetland fisheries which often provide a 'safety valve' for people who cannot access other sources of livelihood (Bene, 2004). The small scale wetland fisheries

provide nutritional security in remote areas that lack adequate supplies of animal protein and sustain the livelihood of landless fishers who can no longer survive by fishing in depleted freshwater bodies (Vass et al., 2009). Although wetlands provide habitat for 40% of all fish species (Arthington et al., 2004), 20% of their biota are amongst the most threatened components of global biodiversity (Smith et al., 2005). This is largely due to human induced environmental degradation. The demand for increased food production to cater for the rising human population and large numbers of undernourished or starving people, especially in the developing countries (Okechi, 2004); have led to widespread conversion of wetlands into farmland. Climate variability which has emerging signals within the River Nile Basin (Di Baldassarre et al., 2011), is likely to have a profound impact on land management practices leading to more changes in land use decisions (Verburg et al., 2011). Consequently, land requirements, reclamation potential and general environmental management are affected (Carvalho et al., 2004).

Many permanently flooded wetlands are open to fishing by anyone (open access) or subject to exclusive communal or individual use rights (Garaway et al., 2006; Martin et al., 2011). Often, wetlands under exclusive access arrangements are exploited less intensely and maintain higher standing stocks of fish than open access wetlands (Lorenzen et al., 1998). The open access wetlands may also be subject to very intensive exploitation of both water and fisheries resources (Garaway et al., 2006). In eastern Uganda, over 10% of Mpologoma River wetland is under cultivation of rice, maize and vegetable to cater for food demand of the increasing population (NEMA, 2004). Simultaneously, there appears to be reduction in the large preferred fish species, *Clarias gariepinus* and *Protopterus aethiopicus* in the Lake Kyoga basin (Muhoozi, 2003). *C. gariepinus* catch reduced from more than 1600 metric tonnes in the 1980s to 1.35 metric tonnes in 2000 (Muhoozi, 2003).

Understanding the effects of land use changes on the fisheries is essential for the management of exploited wetlands (Rientjes et al., 2011). Although there are a few existing models based on observed pattern in temperate areas, scarcity of data for most tropical riverine wetlands limits prediction of the effects of human-induced perturbations on the fish assemblages and catch (Ibanez et al., 2007). Therefore Mpologoma wetland fisheries that support local communities with no access to open lake fisheries and yet it is under intensive exploitation need evaluation. The aim of the study was the assessment of the small scale fishery dynamics in relation to land use in

Mpologoma river wetland. We used comparison of the wetland fish species catch at the wetland sites with different land use patterns. It was hypothesized that the different land use at the wetland sites would affect the fish habitat though water quality variations, leading variation in the wetland fish species catch. The spatial-temporal variation of the wetland fish species catch in Mpologoma riverine wetland was expected.

## MATERIALS AND METHODS

### Study area and sampling sites

Mpologoma river wetland in Uganda (latitude 1°12' N and longitude 34°40' E) extending up to 102 km, discharges 610 million m<sup>3</sup> of water annually into Lake Kyoga complex (Ramsar, 2008). The climate is tropical with rainfall ranging between 1470 - 2300 mm in the longer wet season. The maximum temperature range is 27 – 32°C and the minimum is 16 – 18°C. This permanent wetland is dominated by papyrus (*Cyperus papyrus*) and hippo grass (*Vossia cuspidata*). The fish species of economic importance in the Lake Kyoga complex include *Clarias gariepinus*, *Protopterus aethiopicus*, *Oreochromis leucostictus*, *O. niloticus*, *Bagrus docmak*, *Rastrineobola argentea* and *Tilapia spp* (Vanden-Bossche and Bernacsek, 1990; NaFIRRI, 2007).

Using the Digital Elevation Model of the AVSwat, a map of Mpologoma river wetland with the four differently disturbed study sites was delineated (Figure 1). The main depression which is Mpologoma riverine wetland system consists of a network of small vegetated valley bottoms, fed by 38 sub-catchments. Four study sites with different levels of disturbance were selected along the wetland. Land use cover at each site was derived from Landsat ETM images of July 2011, verified by field survey data. Seven land use classes were identified in 200 hectare polygons area about each site (Table 1). Budumba and Mazuba sites were minimally disturbed with small farms at the edge of the wetland. Kapyani site was highly disturbed with small scale rice and maize farms of acreage of 2 – 6 acres inside the wetland, using low implement agriculture and rain-fed lowland systems (MAAIF, 2009). Nsango site was highly disturbed with a large scale rice scheme occupying over 3,000 hectares of the wetland. Artificial fertilisers, rainfed lowland and irrigation systems were used at the rice scheme.

### Wetland fish assemblage

Fish samples from several fishing techniques were used to determine the wetland fish species composition and fishery production. Experimental fish sampling was done with gill nets hanged in the lagoons, while traps were placed inside the wetland. Gill nets of 2, 2.5 and 3 cm mesh sizes were set in parallel in the lagoon. Ten local basket traps were randomly deployed to catch fish inside the flooded vegetation zone of the wetland. All gear were set at around 7:00 h and retrieved before 14:00 h. This was done to reduce loss of fishing gear to the local fishermen during overnight fishing. On landing, fish samples were counted, total length and weight measured, and records of the gear and effort used at every

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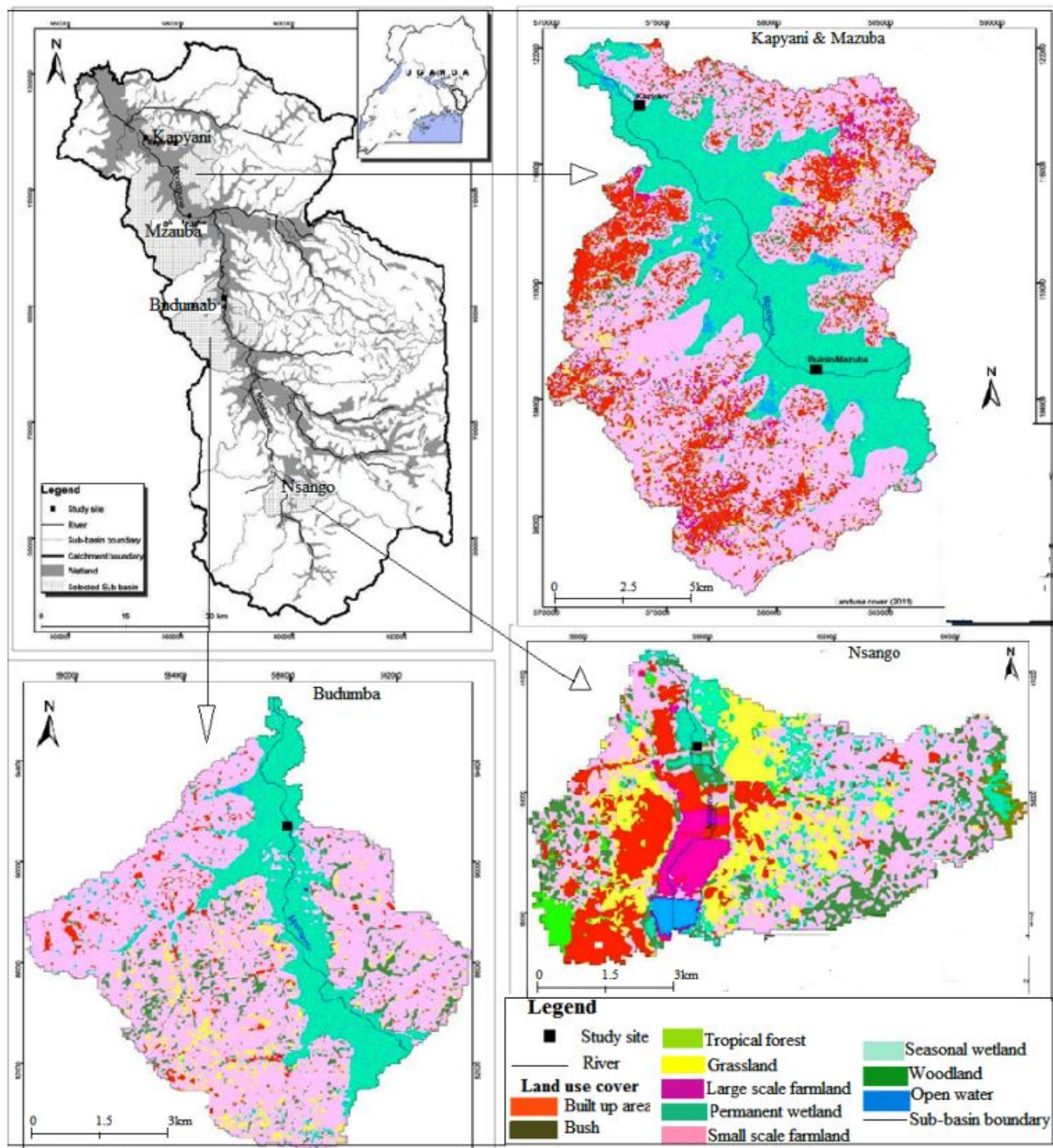


Figure 1. Land-use cover of three sub-basins surrounding study sites in the Mpologoma River catchment, Uganda, in July 2011.

site. Some fish were preserved in 40% ethanol and retained for identification using keys (Greenwood, 1974; Witte and van Densen,

1994). To cater for the seasonal changes in fishery, each site was sampled once a month for 12 months between September

**Table 1.** Land use percentage cover of 200 ha area around study sites in Mpologoma River wetland, Uganda, 2011.

Land use	Mazuba	Budumba	Kapyani	Nsango
	Intact wetland	Less disturbed	Highly disturbed (with small scale farms)	Highly disturbed (Large scale rice scheme)
<b>Man made type</b>				
Built up area	0	0.48	1.52	18.13
Subsistence	0	8.67	55.25	16.18
Large scale farmland	0	0	0.00	16.16
Subtotal cover	0	9.15	56.77	50.47
<b>Natural type</b>				
Permanent wetland	100	90.63	31.21	17.30
Temporary wetland	0	0	10.15	5.58
Woodland	0	0.23	1.38	21.09
Grassland	0	0	0.48	4.31
Subtotal cover	100	90.86	43.22	48.28

2011 and August 2012.

More data on wetland fish species and catch was collected from fishermen landing catches at each site for every sampling day. The local fishermen distributed their fishing effort throughout the study site each trip to sample each portion of the study site each day. At each site, fishermen had their own culture of who fishes where, and regulated the number of fishermen per landing site. Therefore the decision of about where and how to fish was left to the fishermen. The local fishermen dominantly used gill nets (2.5 cm and 3.0 cm mesh sizes) of about 45 m long by 1.5 m deep, fishing lines with varying number of hooks and local basket traps (0.4 by 0.4 by 0.3 m, on average) as fishing gears. Fishing lines consisted of a weight (approximately 2 kg) with varying number of baited hooks mainly set to catch *Protopterus* sp. and *C. gariepinus* within the wetland. Bait materials included pieces of small fish species such as small *Clarias* species, *Tilapia* species, frogs and large insects for hooks, while dead earthworms were for basket traps. Most fishing gear were set at 18 hours and retrieved at 6:00 hours to prepare for the markets. Data on captured species brought to the landing sites were recorded including fish taxa, total length (TL, in centimeters), weight (Wt, in grams), type of gear and effort used. Total length and weight were measured as quickly as possible after the fishermen returned with their catch. For small species such as small *Clarias* sp., *Haplochromis* spp., *Tilapia* spp. and *Barbus* sp., random sub samples were taken to measure standard lengths but their total number in the catch recorded. For large species such as *C. gariepinus* and *Protopterus* sp. groups of similar sizes were counted and sub sampled for measuring their total length and weight to get as much data as possible in the limited time allowed by the fishermen.

#### Physical habitat

To characterise water quality of the wetland sites with different land uses, three water samples were collected from different points (within the wetland, middle of lagoon and edge of the lagoon) at each site. Within the wetland, three water samples were randomly collected close to where traps were placed at each site. Conductivity and pH were determined *in-situ* using a Hanna Instruments HI 9813-6 N Waterproof pH/Ec/TDS/°C meter. Dissolved oxygen and temperature were determined *in-situ* by

Oakton DO 110 meter. Chemical analysis was performed on 0.45 µm membrane filtrate for alkalinity, nitrate-nitrogen and orthophosphate and unfiltered samples for total phosphorus within 48 h of collection according to standard procedures (APHA, 1995).

#### Data analysis

Fish data were summarised into the species composition catch and catch per unit effort (CPUE) for spatial and temporal variation along the wetland. The fishermen usually fished only once a day and therefore species catch was considered as total species catch in kilogram per day. Since the fishery was a multispecies type and uses non-selective fishing gear, for gill nets and traps fishing gear, CPUE was calculated by dividing the catch in grammes of the most dominant fish species caught by the individual gear by the number of hours. Most gillnets were set for less than 5 h and most fisherman had only one net, therefore the units of CPUE of gill nets derived from the mean sizes of gillnets and fishing hours used along the wetland. Most fishermen used locally made basket traps of similar sizes and shape. Therefore the units of CPUE of traps was derived from number of traps and hours used per fisherman. CPUE of lines with hooks was calculated by dividing the catch in grammes of most dominant fish species by the hours spent in fishing considering the mean number of hooks per fisherman. Most fishermen using line hooks in the evening and check on the fish caught early morning. Therefore 12 h were used in the calculation of the hooks CPUE. Due to differences in mean number of hooks per sites, the hooks' CPUE was standardized to 100 hooks per hour. Species richness was tested using Shannon Wiener's index ( $H'$ ) of diversity (Thiebaut, 2006) in the equation;

$$H' = - \sum p_i \ln(p_i),$$

Where,  $p_i$  is the relative abundance of individual fish species.

Statistical analysis on all data was performed using SPSS version16 (IBM ©). All the wetland fish species catch and CPUE were treated as separate dependent variables. Data was log transformed since it was not normally distributed (Kolmogorov-Simonov test ( $p = 0.00$ ) and Skewness of 4.523). One-way ANOVA followed by Tukey's HSD post hoc test was used to test differences



**Table 2.** Mean number of fishermen, fishing gear type per fisherman and boats at one major landing site of each of the differently disturbed sites along Mpologoma river wetland in 2012.

Parameter	Budumba	Mazuba	Kapyani	Nsango
Number of fishermen	22 ± 5	22 ± 4	30 ± 9	17 ± 5
Number of hooks per fisherman	85 ± 34	50 ± 35	64 ± 41	30 ± 17
Number of gill nets per fisherman	1	1	1	1
Number of traps per fisherman	8 ± 3	6 ± 3	5 ± 2	7 ± 3
Number of boats per site	16 ± 4	17 ± 2	13 ± 2	7 ± 2
Mean Catch per day (Kgday <sup>-1</sup> )	29.03 ± 9.66 <sup>a</sup>	21.28 ± 10.46 <sup>a</sup>	24.10 ± 11.70 <sup>a</sup>	2.07 ± 1.62 <sup>b</sup>

The catch values with same superscript are not significantly different at  $P < 0.05$ .

in daily catch among fishing gears, species CPUE, catch and fish length between sites. Using R-statistic software (*R version 3.0.2*; R Development Core Team 2008), non-metric multidimensional scaling (NMDS) was more appropriate in measuring community dissimilarities between study sites along the wetland. The relationship between study sites and water quality parameters was evaluated to ordinate the similarity between sites. Water quality parameters were further fitted to the ordination as vectors to identify the parameters that significantly differentiate the study sites. Stepwise multiple linear regressions with forward selection of variables were used to analyze the relationship between fish catch and water quality parameters.

## RESULTS

### Fish species composition and catch

Data on a total 5137 fish specimens were collected from all study sites over the sampling period. Six fish species dominated the wetland fish community. *C. gariepinus*, *C. liocephalus*, *C. alluaudi*, *P. aethiopicus*, *O. leucostictus*, *T. zillii* and several unidentified *Haplochomis* species were observed at all site along the wetland. *Synodontis afrofisheri* was observed only at highly disturbed Kapyani site close to Lake Lemwa. The number of species ranged from seven at the highly disturbed sites to nine at the less disturbed sites and the mean Shannon Wiener index of diversity was  $5.4 \pm 1.2$  per site. During the wet season months, a higher number of species was recorded than during the dry season months. For instance, the species richness index of 4.94 and 4.81 were realized in January and February, while 6.77 and 6.69 were realized in September and October respectively at less disturbed Nsango site.

Wetland fishery production was estimated to be 57 kg per ha per year. The number of fishermen ranged from 12 at the highly disturbed Nsango site to 27 at the less disturbed Budumba site (Table 2). Three fishing gear (gill nets, line hooks and basket traps) were dominantly used at all sites. Many fishermen used line hooks with a range of 13 hooks at the highly disturbed Nsango site to over 119 hooks at the less disturbed Budumba site. At the less disturbed Budumba and Mazuba sites, the fishermen had

a high number of hooks to catch as much fish as possible within in the intact wetland. Traps and gill nets were used minimally at all sites. During the rainy season, gillnets with 3.0 cm mesh size harvested more fish than other gears. Hooks were dominantly used during the dry season. More than 50% of the catch comes from the hooks fishery. Gill nets with 3.0 cm mesh size was the second most important, followed by the gill nets with 2.5 cm mesh size and traps (Figure 2). The number of hooks, gill nets of 2.5 cm mesh size and traps catch did not vary between season ( $p = 0.001$ ). But among sites, the number of hooks were significantly higher at the less disturbed Budumba site than at the highly disturbed Nsango site ( $p = 0.023$ ). The catch varied among the dominant fishing gears used. Significantly higher catch was realized by the use of line hooks than all other fishing gears ( $p = 0.001$ ). The line hooks' mean catch of  $11423 \pm 6936$  g/day was observed in the wet season and  $14863 \pm 9558$  g/day observed during the dry season which high compared to  $3294 \pm 3108$  and  $4860 \pm 4392$  g/day the wet and dry season gill nets' catch respectively. There were temporal and spatial differences in the catch of individual fish species. Relatively higher catch was observed in the dry season than in the wet season and more at the less disturbed sites than at the highly disturbed sites (Figure 3). *C. gariepinus* and *P. aethiopicus* dominated the fishery by catch weight with a range of 0.45 kg per day at the highly disturbed Nsango site to 38.67 kg per day at the less disturbed Budumba site and 0.245 to 20.18 kg per day, respectively (Table 2). Catch at Nsango was significantly lower than that of other sites (Tukey's HSD test;  $p < 0.05$ ). Higher catch of both *C. gariepinus* and *P. aethiopicus* species was recorded during the dry months (January, February, July and August, Figure 3). Significantly higher catch of both species was recorded at the less disturbed sites (Budumba and Mazuba) than at the highly disturbed site (Nsango) at  $p = 0.05$  (Table 3). The disturbed Kapyani site had relatively high *C. gariepinus* catch almost the whole sampling period. The catch of small *C. liocephalus* and *C. alluaudi* was higher at the highly disturbed site than at the less disturbed sites (Figure 4).

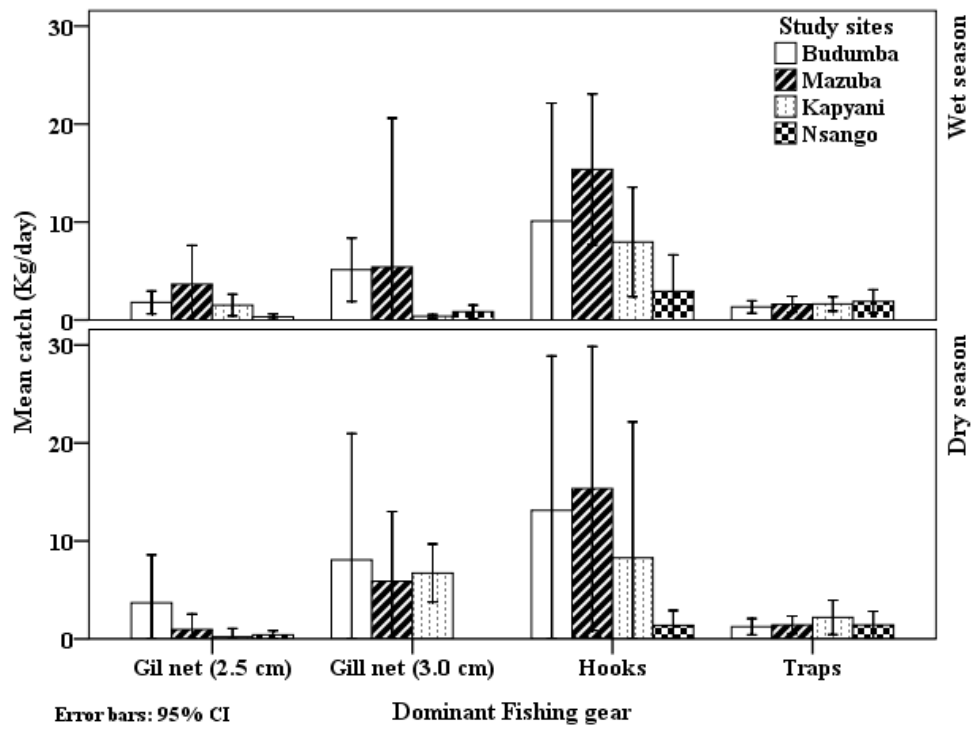


Figure 2. Seasonal mean catch of the major fishing gear at the four sites along Mpologoma wetland between September 2011 to August 2012.

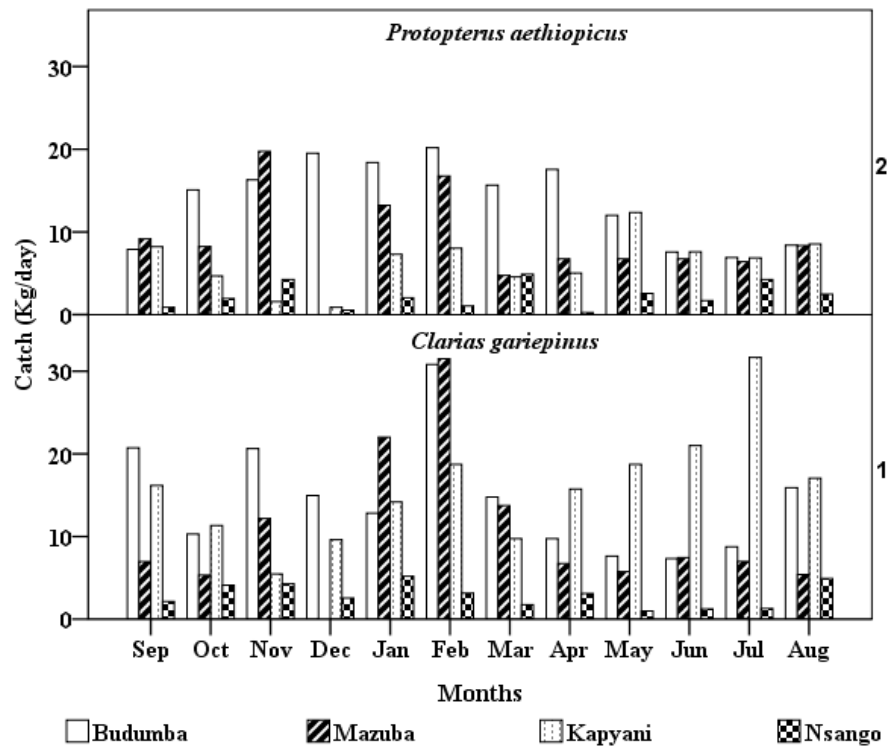
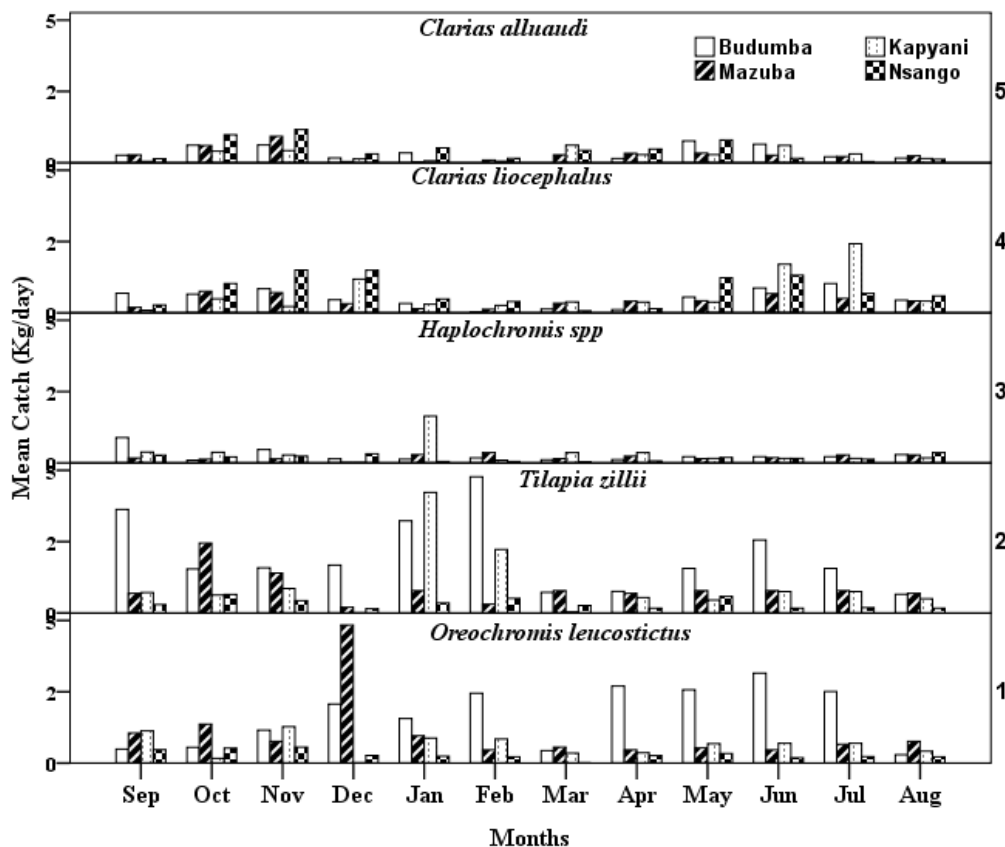


Figure 3. Mean catch of the big fish species in Mpologoma wetland fishery between September 2011 to August 2012.

**Table 3.** Mean catch (Kg/day, ± SD) of major fish species at differently disturbed sites along Mpologoma river wetland during the sampling period.

Fish species	N	Budumba	Mazuba	Kapyani	Nsango
<i>Oreochomis leucostictus</i> (Trewavas, 1933)	565	1.56 ± 1.07 <sup>a</sup>	1.13 ± 1.51 <sup>a</sup>	0.61 ± 0.41 <sup>a</sup>	0.29 ± 0.15
<i>Tilapia zillii</i> (Garvais, 1848)	703	1.92 ± 1.28	0.86 ± 0.58 <sup>a</sup>	0.93 ± 1.14 <sup>a</sup>	0.32 ± 0.18
<i>Haplochromis spp</i>	1115	0.26 ± 0.25 <sup>a</sup>	0.19 ± 0.09 <sup>a</sup>	0.33 ± 0.42 <sup>a</sup>	0.19 ± 0.13 <sup>a</sup>
<i>Clarias liocephalus</i> (Boulenger, 1902)	788	0.50 ± 0.32 <sup>a</sup>	0.42 ± 0.21 <sup>a</sup>	0.66 ± 0.70 <sup>a</sup>	0.75 ± 0.52 <sup>a</sup>
<i>Clarias alluaudi</i> (Boulenger, 1906)	419	0.37 ± 0.24 <sup>a</sup>	0.30 ± 0.25 <sup>a</sup>	0.27 ± 0.19 <sup>a</sup>	0.42 ± 0.36 <sup>a</sup>
<i>Clarias gariepinus</i> (Burchell, 1815)	1062	14.64 ± 6.77 <sup>a</sup>	11.28 ± 8.39 <sup>a</sup>	15.88 ± 6.56	3.05 ± 1.62
<i>Protopterus aethiopicus</i> (Heckel, 1851)	598	13.38 ± 5.04 <sup>a</sup>	9.72 ± 4.78 <sup>a</sup>	6.47 ± 3.09 <sup>a</sup>	2.25 ± 1.46

Values in the same row with the same superscript are not significantly different (p < 0.05).



**Figure 4.** Fish catch of the small fish species at different sites along Mpologoma river wetland between September 2011 to August 2012.

The mean CPUE for the major commercial fish species varied with fishing gear, season and study site. The CPUE for *C. gariepinus* and *Protopterus sp* was higher with the use of hooks, at the less disturbed sites than that of other fishing gear, particularly the highly disturbed Nsango site (Table 4). At the less disturbed Budumba site, mean CPUE for *C. gariepinus* was higher (1.31

Kg100 hooks<sup>-1</sup>h<sup>-1</sup>) in the dry season as compared to 0.90 Kg 100hooks<sup>-1</sup>h<sup>-1</sup> recorded during the wet season. CPUE for the two large fish species at highly disturbed Nsango site was significantly different from that of the other sites (Tukey's HSD test; p < 0.05). However, the highly disturbed Kapyani site CPUE (4.50 Kg 100hooks<sup>-1</sup>h<sup>-1</sup>) was higher than the other highly disturbed Nsango site

**Table 4.** Mean catch per unit effort (CPUE) for the major commercial fish species/groups at each differently disturbed site along Mpologoma wetland during both the dry and wet season between September 2011 to August 2012.

Gear type	Species	Units of CPUE	Dry season				Wet season			
			Budumba	Mazuba	Kapyani	Nsango	Budumba	Mazuba	Kapyani	Nsango
GN 2.5	<i>Haplochomis</i> spp	Kg 45 m <sup>-1</sup> h <sup>-1</sup>	0.03	0.00	0.00	0.10	0.13	0.04	0.01	0.12
	<i>C. gariepinus</i>	Kg 45 m <sup>-1</sup> h <sup>-1</sup>	0.20	0.00	0.53	0.08	0.92	0.20		
	<i>Protopterus</i> sp	Kg 45 m <sup>-1</sup> h <sup>-1</sup>	0.40	0.00			0.29			
	Small <i>Clarias</i> spp	Kg 45 m <sup>-1</sup> h <sup>-1</sup>			0.45					
	<i>Tilapia</i> spp	Kg 45 m <sup>-1</sup> h <sup>-1</sup>	0.85	0.22	0.59	0.23	0.45	0.54	0.20	0.15
GN 3.0	<i>C. gariepinus</i>	Kg 45 m <sup>-1</sup> h <sup>-1</sup>	0.35	0.40	1.60		0.46	0.49	0.20	0.36
	<i>Haplochomis</i> spp	Kg 45 m <sup>-1</sup> h <sup>-1</sup>					0.07			
	<i>Protopterus</i> sp	Kg 45 m <sup>-1</sup> h <sup>-1</sup>	0.52	0.57	0.90		0.38	0.20	0.06	
	<i>Tilapia</i> spp	Kg 45 m <sup>-1</sup> h <sup>-1</sup>	0.13	0.14			0.46	0.17		0.47
Hooks	<i>C. gariepinus</i>	Kg 100hooks <sup>-1</sup> h <sup>-1</sup>	1.31	1.10	4.50	1.20	0.90	1.85	0.76	1.20
	<i>Protopterus</i> sp	Kg 100hooks <sup>-1</sup> h <sup>-1</sup>	0.86	1.05	1.28	0.54	1.32	1.88	0.81	1.09
	Small <i>Clarias</i> spp	Kg 100hooks <sup>-1</sup> h <sup>-1</sup>	0.16	0.20	0.33	0.27	0.15	0.16	0.11	0.26
Traps	<i>Barbus</i> sp	Kg trap <sup>-1</sup> h <sup>-1</sup>	0.04	0.02		0.09		0.02		0.03
	<i>C. gariepinus</i>	Kg trap <sup>-1</sup> h <sup>-1</sup>	0.04	0.06	0.11	0.06	0.09	-	0.11	0.08
	<i>Haplochomis</i> spp.	Kg trap <sup>-1</sup> h <sup>-1</sup>	0.01	0.04	0.09	0.23	0.03	0.14	0.05	0.07
	<i>Protopterus</i> sp.	Kg trap <sup>-1</sup> h <sup>-1</sup>	0.05	0.12	0.12	0.05	0.06	0.12	0.12	0.07
	Small <i>Clarias</i> spp.	Kg trap <sup>-1</sup> h <sup>-1</sup>	0.16	0.11	0.18	0.19	0.20	0.15	0.15	0.24

(1.20 100hooks<sup>-1</sup>h<sup>-1</sup>) in the dry season. The CPUE for *C. gariepinus* and *Protopterus* sp. showed an increasing trend during the dry months (Figure 5). While the CPUE of small fish species (*C. alluaudi*, *C. liocephalus*, *Haplochomis* spp and *Barbus* sp) did not vary significantly between season and sites (p = 0.05).

**Fish size**

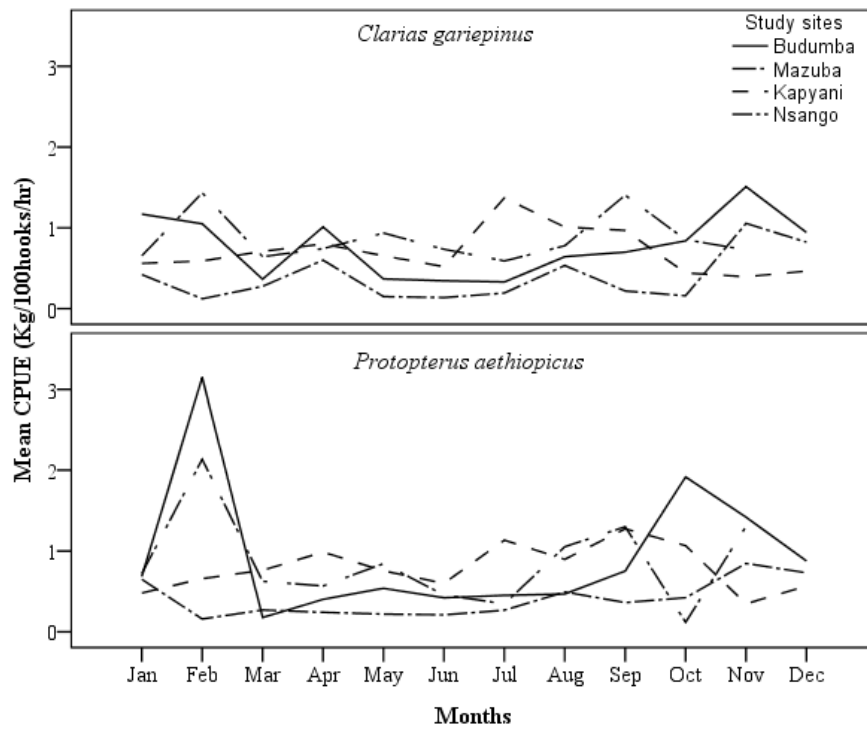
There were variations in *C. gariepinus* and *P.*

*aethiopicus* total length in the wetland with a range of 12 to 135 cm and 16 to 151 cm respectively. The mean total length of *C. gariepinus* at Budumba and Mazuba was 47.27 ± 20.47 and 45.32 ± 16.76 cm, respectively. While at the highly disturbed sites (Kapyani and Nsango), the mean total length was 41.19 ± 21.85 and 27.33 ± 10.98 cm, respectively. Larger fish individuals of both species were caught during the wet season (April, May and October; Figure 6). The length of these two species was significantly lower at highly disturbed Nsango site than that of

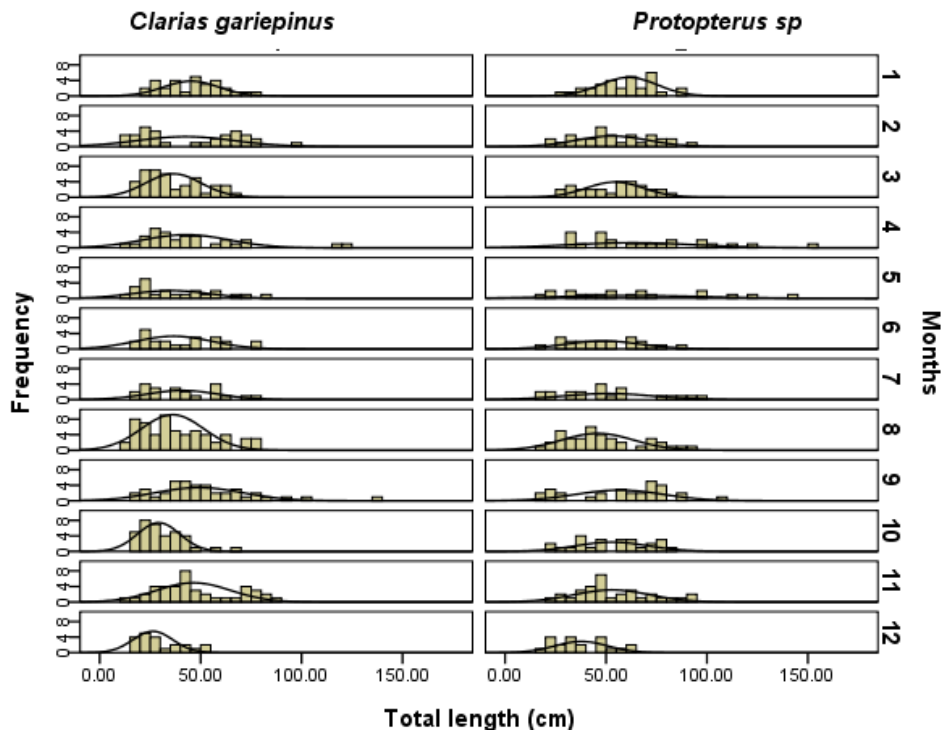
the less disturbed sites (p < 0.01; Figure 7). The less disturbed sites had larger fish even among the *Oreochomis* and *Tilapia* species than highly disturbed sites. However, the small fish species behaved differently. *C. liocephalus* total length ranged from 6.0 to 26.4 cm at Budumba and from 9.5 to 28.5 cm at Nsango.

**Environmental data**

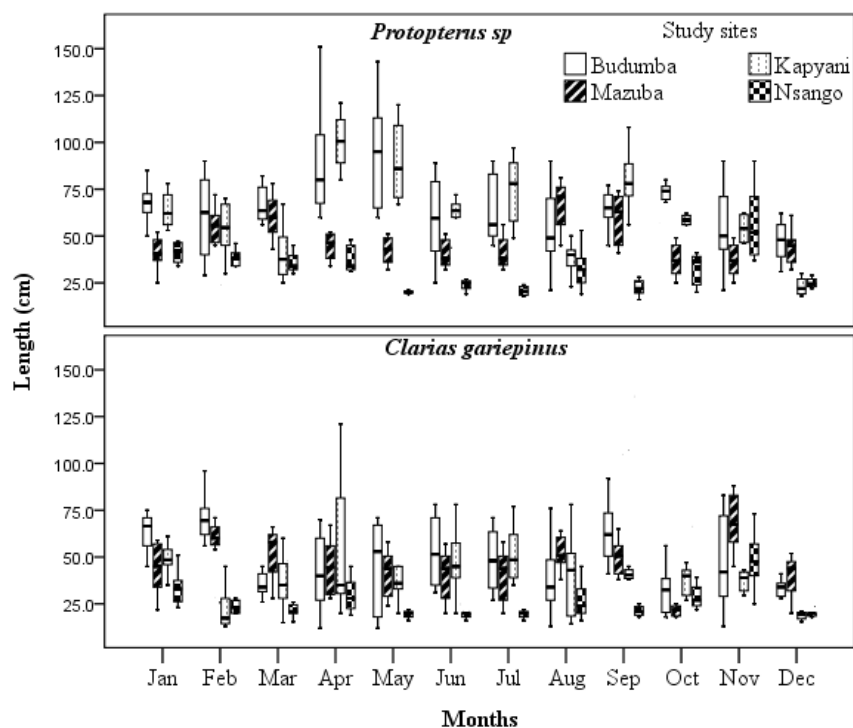
The water quality parameters varied in space and



**Figure 5.** Monthly mean catch per unit effort (CPUE) of the two large fish species at the four differently disturbed sites along Mpologoma wetland between September 2011 to August 2012



**Figure 6.** Length frequency distribution of two large fish species of Mpologoma river wetland fishery between September 2011 to August 2012.



**Figure 7.** Mean total length of the large fish species caught at the differently disturbed sites along Mpologoma river wetland between September 2011 and August 2012.

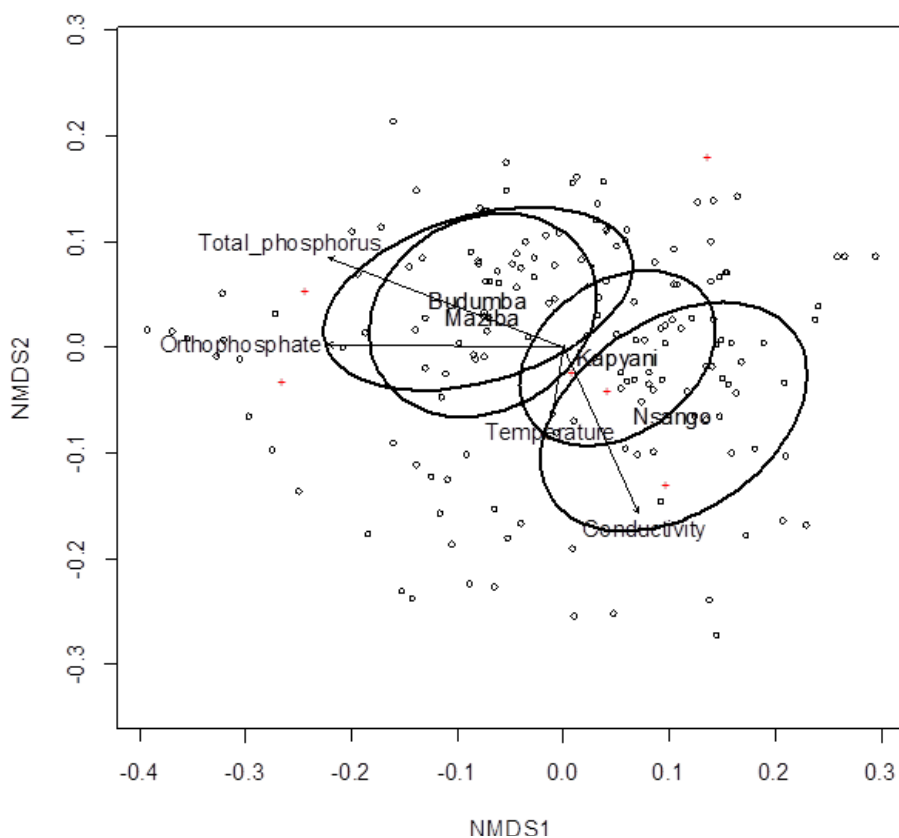
**Table 5.** Mean ( $\pm$  STD) of water quality parameters of fish habitats (inside the wetland) at the different study sites along Mpologoma River wetland (September 2011 - August 2012).

Parameter	Budumba	Mazuba	Kapyani	Nsango
DO ( $\text{mg l}^{-1}$ )	$1.35 \pm 1.03^a$	$1.98 \pm 1.26^a$	$1.58 \pm 0.67^a$	$0.96 \pm 0.76$
Temp ( $^{\circ}\text{C}$ )	$23.75 \pm 1.72$	$24.53 \pm 0.81$	$25.35 \pm 1.31$	$24.18 \pm 1.49$
Conductivity ( $\mu\text{S/m}$ )	$152 \pm 32.1^a$	$161 \pm 35.2^a$	$218 \pm 53.1^b$	$351 \pm 55.4^b$
$\text{OPO}_4^{3-}$ ( $\text{mg l}^{-1}$ )	$0.28 \pm 0.26^a$	$0.27 \pm 0.23^a$	$0.13 \pm 0.12^b$	$0.14 \pm 0.34^b$
TP ( $\text{mg l}^{-1}$ )	$0.67 \pm 0.44^a$	$0.62 \pm 0.39^a$	$0.29 \pm 0.27^b$	$0.23 \pm 0.19^b$
Water depth (m) during the dry season	$0.52 \pm 0.27$	$0.45 \pm 0.14$	$0.30 \pm 0.15$	$0.35 \pm 0.14$

Values in the same row with the same superscript are not significantly different.

time along the wetland. Conductivity ranged from 119.9  $\mu\text{S/m}$  at less disturbed Budumba site to 406.4  $\mu\text{S/m}$  at the highly disturbed Nsango site. Conductivity at the less disturbed sites was significantly lower than that of disturbed sites and higher during the dry months. Dissolved oxygen (DO) within the papyrus ranged between 0.20  $\text{mg l}^{-1}$  at highly disturbed site to 3.24  $\text{mg l}^{-1}$  at less disturbed site (Table 5). DO was high during the wet season months (April, May, October and November) with a range of 2.2 to 4.4  $\text{mg l}^{-1}$  in the mid river. DO was low in the dry season months (January, February, June

and July) with a range of 0.6 to 1.8  $\text{mg l}^{-1}$  in the mid river section. Nitrate levels were very low to undetectable levels at all sites during the wet season while in the dry season, it ranged from 0.01 to 0.12  $\text{mg l}^{-1}$  at the less disturbed sites and 0.03 to 0.18  $\text{mg l}^{-1}$  at the disturbed sites. Orthophosphate and total phosphorus ranged from 0.041 to 1.15  $\text{mg l}^{-1}$  and 0.093 to 1.80  $\text{mg l}^{-1}$  respectively in the wetland. From the NMDS analysis, the resulting ordination was two dimensional with final stress of 17.7 at  $p < 0.05$ . The less disturbed Budumba and Mazuba sites were identical as the distance between their circles was



**Figure 8.** Non-metric multidimensional scaling plot of study sites along Mpologoma river wetland. Visually fit ellipses were drawn around sites that had similar levels of water quality parameters that were significantly different between sites.

**Table 6.** Environmental vector fitting of the NMDS analysis of the water quality parameters of the different study sites.

Water quality parameters	NMDS1	NMDS2	$r^2$	Pr(>r)
Dissolved oxygen	-0.95645	-0.29191	0.0150	0.316
Temperature	-0.15069	-0.98858	0.0651	0.07 *
Conductivity	0.41252	-0.91095	0.4269	0.001 ***
Orthophosphate	-0.99996	0.00869	0.7077	0.001 ***
Total phosphorus	-0.93377	0.35788	0.8128	0.001 ***

Significant codes: '\*\*\*', 0'; \*\*0.001; \*0.01. P values were based on 999 permutations.

close to zero, while the highly disturbed Nsango site associated with a large scale rice scheme was different from the less disturbed sites as the distance between their circles was larger than zero (Figure 8). The vector analysis showed that conductivity, orthophosphate and total phosphorus were significantly important in differentiating the study sites all at  $r^2$  of 0.43, 0.71 and 0.81 respectively, all at  $P < 0.001$  (Table 6).

There was a significant relationship between fish catch

and water quality parameters. A strong spearman rank correlation ( $\rho' = 0.501$  and  $0.348$ ;  $p < 0.05$ ) between *C. gariepinus* catch with conductivity and orthophosphate respectively was realised. *P. aethiopicus* catch was significantly correlating with conductivity, orthophosphate and total phosphorus ( $\rho' = 0.510$ ,  $0.465$  and  $0.441$ ;  $p < 0.01$  respectively). With stepwise multivariate linear regression, *P. aethiopicus* catch was significantly related to conductivity and orthophosphate ( $R^2 = 0.544$ ;  $p < 0.01$ ;

catch = -13.214 - 0.023 conductivity + 16.69 orthophosphate). No significant relation was realized between water parameters and the small fish species catch and CPUE.

## DISCUSSION

The wetland is a critical refuge for a subset of Lake Kyoga fish species given the high number of similar fish species recorded in the wetland compared to those reported in the open Lake Kyoga. *C. gariepinus*, *P. aethiopicus*, *O. leucostictus* and *Tilapia* spp. which are important Lake Kyoga fish species (NaFIRRI, 2007), were also recorded in the wetland. High diversity, similarity and endemism stem largely from the fact that nearby fresh waters were once connected by heavy floods or drainage free of barriers that enabled dispersal of fish species (Olden et al., 2010). Barriers later maintained fish species in different parts of the riverine wetland. As level of wetland disturbance increase in certain areas of the wetland, the general similarity in species was still maintained in the wetland and this was due to the fact that some fish species are considered relatively tolerant to pollution. These included *Oreochromis* species (Raburu and Masese, 2010), *P. aethiopicus*, *C. gariepinus* and *C. alluaudi* (Timmerman and Chapman, 2004). Normally reduction in species richness and abundance is expected along a degradation gradient (Raburu and Masese, 2010) and indeed at highly disturbed Nsango site, agricultural activities degraded the fish habitats that even tolerant species declined. During the relatively poor water quality periods (high conductivity and low dissolved oxygen), particularly in the dry months, at Nsango site the lowest number of fish species was recorded compared to other sites..

The Mpologoma wetland production estimate was in the order of magnitude of African floodplain production. Lightly exploited floodplain river systems produce about 40 - 60 kg ha<sup>-1</sup> yr<sup>-1</sup> of fish (Welcomme, 1985), while highly exploited tropical floodplains produce estimates more at 110 - 160 kg ha<sup>-1</sup> yr<sup>-1</sup> of fish (Bayley, 1988). The high wetland production estimated was attributed to the increased exploitation rate to cater for the increasing need to diversify livelihoods along the wetland. The complex relationship between catch (fish abundance) and effort (function of fishermen's behaviour) is what controls the catch per unit of effort (Lopes, 2011). On average, the fishermen spent almost the same time span fishing both in wet and dry season, therefore the differences in CPUE resulted from the variation in fish abundance with time at the sites. Despite the few to no full time fishermen at all sites, the fishers were able to access distant less exploited areas with abundant fish resources particularly at the less disturbed sites leading to high catch and CPUE. The fishing gears used also contributed to the

variation in catch and CPUE. The record of high number of hooks per fisherman at the less disturbed sites indicated the importance of this gear to achieving high catch and CPUE. The reliability of fishing gear CPUE as an index of fish density depends on fish activity, gear selectivity, avoidance and the morphology of the fishes (Olin et al., 2010). This explained the application various fishing gear that enabled exploitation of the various fish species at the different sites, during different seasons in the wetland.

Fish species abundance is influenced by physical and chemical composition of water (Randle and Chapman, 2004), habitat size and diversity (Budy et al., 2008), and water flow patterns into the wetland (Vorwerk et al., 2009). The differences in wetland fish species abundance and catch were governed primarily by water quality parameter variation among sites, given the strong correlation between catch and conductivity at the sites. This agreed with earlier studies on floodplain fisheries which highlighted dissolved oxygen, conductivity, pH and water depth as major determinant factors to fish abundance (Louca et al., 2009). Highly disturbed sites' conductivity and dissolved oxygen levels were similar to those of highly studied polluted Nakivubo wetland in Uganda (Kansiime et al., 2007). Wetland clearing for agriculture results in dramatic alteration of the river flood curve which, leads to decrease in both the amplitude and duration of flood regime. The wetland clearing also increases in evapotranspiration which, lead to increased salts in the water. These have pronounced impact such as high conductivity, alterations of vegetation species and cover, and decreased connectivity in wetland lagoons (Louca et al., 2009). Sustained increase in conductivity compounded by high sedimentation levels led to negative implications on the fish ecology (Chapman et al., 2003). The large rice scheme irrigation activities involve application fertilizers near Nsango site seem to have affected the water quality which, explain the reduced abundance of large fish species. Lungfish (*Protopterus* sp.) decline reflects the interaction of overexploitation and large-scale conversion of wetlands to agricultural land for the past few decades (Goudswaard et al., 2002). Such species with preferences for lower conductivities and high dissolved oxygen disappear from the wetland once these conditions persist (Goudswaard et al., 2002; Louca et al., 2009). This explains the low *C. gariepinus* and *Protopterus* species abundance at highly disturbed Nsango where those harsh conditions were observed.

Higher fish species composition abundance was recorded at the downstream disturbed Kapyani site and this was attributed to a number of factors. The interaction between the river and lake hydrology which modifies the fish habitats with modified vegetation and deeper waters (Cooper et al., 2007) allowing more fish to coexist, both wetland and open water dwelling species, despite the level of disturbance. The site was permanently connected



to the nearby lakes Nakuwa and Lemwa. Also habitat recovery from disturbance during the flooding season is associated with increased food resources (Morris et al., 2007; Vorwerk et al., 2009), resulting in high fish abundance. Furthermore, wet season rice crop when cultivated as a largely rainfed crop and have little land engineering, causes less impacts on water quality and later on fish (Nguyen-Khao et al., 2005).

Temporal variation in fish species abundance and catch in the wetland was also attributed to their reproductive traits and predator avoidance factors. Low abundance of all *Clarias* species at beginning of the rainy season along the wetland was due to their breeding cycle (Offem et al., 2010). *T. zillii* spawn at the end of the dry season (El-Sayed and Moharram, 2007) and this could explain their low abundance during the dry season in the wetland. The observed high catch at Budumba and Kapyani during the dry season was due to the high water level maintained at these two sites which, offered refuge for fish avoiding harsh conditions. *Oreochromis* sp. spawn anytime but larger quantities are observed during the rainy season (Melcher et al., 2012). Variation of small fish species abundance which breed throughout the year was attributed to avoidance of predators. High abundance of haplochromines in highly polluted areas is due to the non-avoidance of predators in turbid waters while their low abundance in less polluted areas is due to avoidance in clearer waters (Ogutu-Ohwayo, 1990).

Availability of abundant food during the rainy season is also an important factor responsible for the temporal variation in wetland fish (Offem et al., 2010). Rainy conditions lead to higher detritus, softer decomposing plant materials and low phosphorus favour in high abundance of benthic invertebrates (Hansson et al., 2005) which are important food for mainly the small fish species. Disruptions in the food base caused by alterations in water quality, particularly at highly disturbed sites, have been found to lead to higher percentage of omnivores (generalists) and a decrease in the proportions of insectivores and carnivores (Morris et al., 2007). *C. gariepinus* which is predatory (Raburu and Masese, 2010) was less abundant than *C. liocephalus*, an omnivore at highly degraded sites. Thus, feeding and reproductive strategies are among the divergent life-history characteristics that make riverine fish species respond to annual flood pulse and short-term environmental disturbances in different ways (Winemiller, 2005; Montaña et al., 2007).

The relationship between land use and small scale fishery was realized though strong relation between fish species catch and water quality parameters. The results should be of interest to resource managers because land use changes in the wetland have the potential to drastically affect the water quality, negatively impacting the production of large commercial fish species of such a small scale fishery. The wetland ecological shift phase

need to be established in order for policy makers to regulate the land use change rate which may have potentially irreversible effects to both small and large fish species of this small scale fishery.

### Conflict of Interests

The author(s) have not declared any conflict of interests.

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*Full Length Research Paper*

# Evaluation of groundwater suitability for drinking, domestic and irrigational purposes: A case study of Makurdi metropolis and environs, Benue State, North Central Nigeria

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A study of groundwater samples from Makurdi metropolis and environs was carried out to assess its suitability for drinking, domestic and irrigational purposes. The chemistry of groundwater within the study area with respect to pH, total dissolved solids (TDS),  $\text{NH}_3^-$ ,  $\text{NO}_3^-$ ,  $\text{Cl}^-$ ,  $\text{Na}^+$ ,  $\text{K}^+$ ,  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{HCO}_3^-$ ,  $\text{SO}_4^-$ ,  $\text{Fe}^{3+}$ ,  $\text{Cu}^{2+}$ ,  $\text{Mn}^{2+}$  and  $\text{Zn}^{2+}$  was used to determine its suitability for drinking. Some parts of the study area have elevated concentration of TDS, magnesium, nitrate, sulphate, copper, manganese and iron and which are considered unsafe for drinking and some domestic uses based on the standard organization of Nigeria (SON, 2007) and the World health organization (WHO, 2011) guideline concentration for drinking water. Sodium adsorption ratio (SAR), percentage sodium (Na%) and bicarbonate hazard have been studied to evaluate the suitability of the groundwater for irrigation purpose. This study show that groundwater within the area is safe for irrigation with respect to sodium adsorption ratio but a good number of the samples had high values of bicarbonate hazard and percentage sodium, and are unsuitable for irrigation.

**Key words:** Irrigation, groundwater, Makurdi metropolis, suitability.

## INTRODUCTION

Groundwater is the largest source of fresh water in the world. It is of major importance to civilization, being the largest reserve of natural drinkable water that can be used by humans. Groundwater occurs in almost all geological formations and the natural filtering effect of these geologic materials often makes groundwater preferable to surface water for many purposes.

The chemical composition of groundwater is related to the soluble products of rock weathering, decomposition

and dissolution of organic matter and changes over time (Raghunath, 2007). The chemical quality of groundwater depends on the characteristics of the soil and rocks through which it has percolated and also on its resident time in these rocks. Some constituents of groundwater are also derived from the atmosphere as rain takes some atmospheric gases and ions into solution. Others have resulted from anthropogenic sources such as agriculture, industrial and improper disposal of refuse and sewage

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which often results in groundwater pollution. Water pollution in Makurdi metropolis and environs results mainly from human activities which results in the deterioration of the physical, chemical and biological properties of water (Akuh, 2014). The population depends mostly on groundwater abstracted through hand-dug wells and boreholes as their source of domestic water supply, farmers in the rural areas also depend on groundwater from wells to irrigate their small farms during the dry season. For effective management of the available water resources, an evaluation of the quantity as well as the quality of water for various purposes has to be carried out. Irtwange and Sha'ato (2009) reported 0.22 mg/l TDS, 60 mg/l  $\text{Cl}^-$ , 28.81 mg/l  $\text{SO}_4^{2-}$ , 1.36 mg/l  $\text{Zn}^+$  and 200 mg/l  $\text{Na}^{2+}$  for groundwater from a borehole located at a solid waste disposal site in Makurdi. Idoko (2010) reported iron concentration ranging from 0.03 to 2.38 mg/l for groundwater in Benue State during the rainy season and values ranging from 0.01 to 5.02 mg/l during the dry season. He attributed the elevated iron concentration to geology and confirmed higher concentration in areas with lateritic soil. Edet et al. (2011) reported concentrations of 6136.75 mg/l  $\text{Na}^+$ , 243.15 mg/l  $\text{K}^+$ , 390.58 mg/l  $\text{Ca}^{2+}$ , 70.80 mg/l  $\text{Mg}^{2+}$ , 10278.75 mg/l  $\text{Cl}^-$  and 406.05 mg/l  $\text{HCO}_3$ .

This study was conducted to determine the physico-chemical properties of groundwater in Makurdi metropolis and environs and evaluate its suitability for drinking, domestic and irrigational purposes.

### The study area

Makurdi is located in Benue State, north central Nigeria. It is bounded by latitudes  $8^{\circ}30'00''$  to  $8^{\circ}41'00''\text{N}$  and longitudes  $7^{\circ}40'00''$  to  $7^{\circ}50'00''\text{E}$  (Figure 1). It is located within the middle Benue Trough and covers an area of about  $370 \text{ km}^2$ . It is accessible by the Makurdi-Lafia road and intra state roads such as the Makurdi-Otukpo road, Makurdi-Gboko road as well as footpaths with many rural road networks linking the rural areas to Makurdi town. The annual rainfall depth ranges from about 1,200 to 1,500 mm with an average depth of about 1350 mm. Temperatures are generally very high during the day, particularly in March and April. Along the river valleys, these high temperatures together with high relative humidity produce debilitating weather conditions. Makurdi records average maximum and minimum daily temperatures of 35 and  $21^{\circ}\text{C}$  during the rainy season and 37 and  $16^{\circ}\text{C}$  during the dry season, respectively (Lower Benue River Basin Development Authority).

### Geology and hydrogeology of the study area

Much of Benue State within which Makurdi is located falls within the intra cratonic sedimentary basin known as the

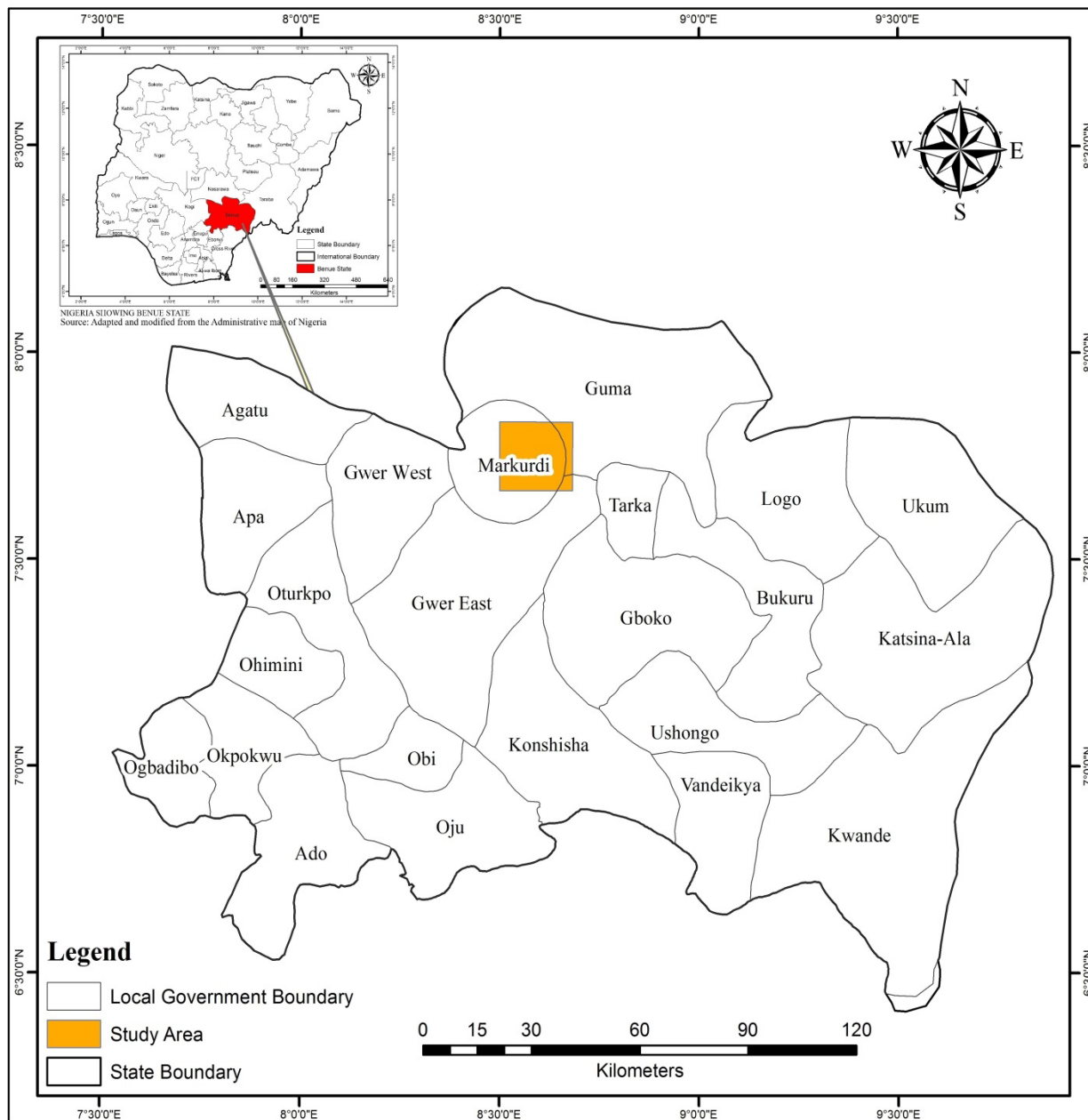
Benue Trough which is believed to be structurally developed. The Benue Trough is a linear sedimentary basin which is filled with Cretaceous rocks whose ages range from Middle Albian to Maastrichtian. It is bounded on either side by granite and gneisses which make up the crystalline basement (Cratchley and Jones, 1965). Many others like Najime (2010), Obaje (1994) and Zaborski (1998) described the Benue Trough as a NE-SW trending intracratonic basin ranging between 150 km wide and 800 km long. Lithologies identified in the study area (Makurdi metropolis and environs) include: the Ezeaku shale, the Makurdi Formation, Awe formation, alluvial deposit and pockets of basalt.

The Ezeaku Formation consists of thick flaggy calcareous and non-calcareous shale, sandy or shaly limestone and calcareous sandstones. It is reported to be 304.8 m thick in this region and ranges up to 609.6 m towards the south of the state (Offodile, 1989).

The Makurdi formation consists of a thick mass of current bedded coarse grained deposit described as the Makurdi Sandstone (Figure 2) Geological and mineral resources map of Benue State adopted from Nigerian Geological survey agency (NGSA) 2006. Akuh (2014) described this sandstone as well sorted, medium to coarse grained, grain supported and texturally immature subarkose with minor clay rim cement and 3 - 4% porosity. It is highly indurated and cemented mainly by quartz and iron oxide (Adanu, 1981). The Makurdi Sandstone is the most important aquifer in the middle Benue trough. This aquifer is almost impermeable in places; especially the western part of Makurdi metropolis where its compact and indurated nature makes it difficult for the inhabitants to sink hand dug wells into it as the wells are terminated when the sandstone is encountered. Where fractured or less indurated, the formation is usually less compacting, more permeable and has better prospect as an aquifer (Offodile, 2002). Adanu (1981) obtained hydraulic conductivity values of 0.132, 1.73, 3.5 and average porosities of 17.3, 27.8 and 31.3% for various samples of the Makurdi sandstone. These properties influence the rate at which this aquifer is recharged.

The usefulness of the Makurdi Sandstone as a potential groundwater reservoir depends on its secondary permeability derived from weathering and fracturing (Offodile, 2002). It reported yields of 8.2 L/s from a borehole drilled into the Makurdi Sandstone at the Army cantonment, yields between 2.5 and 3.9 L/s were obtained in Aliade and 8.7 L/s from the borehole at the Lower Benue River Basin Estate. Recharge into the aquifer is both direct and indirect. Where the aquifer is uncovered and permeable, the recharge is direct from precipitation, by seepage and along fractures and joints. This is the case in Yaiko and Airport village, indirect recharge to this aquifer is by infiltration through weathered materials overlying the Sandstone aquifer (Adanu, 1981).

The Awe Formation was deposited as passage



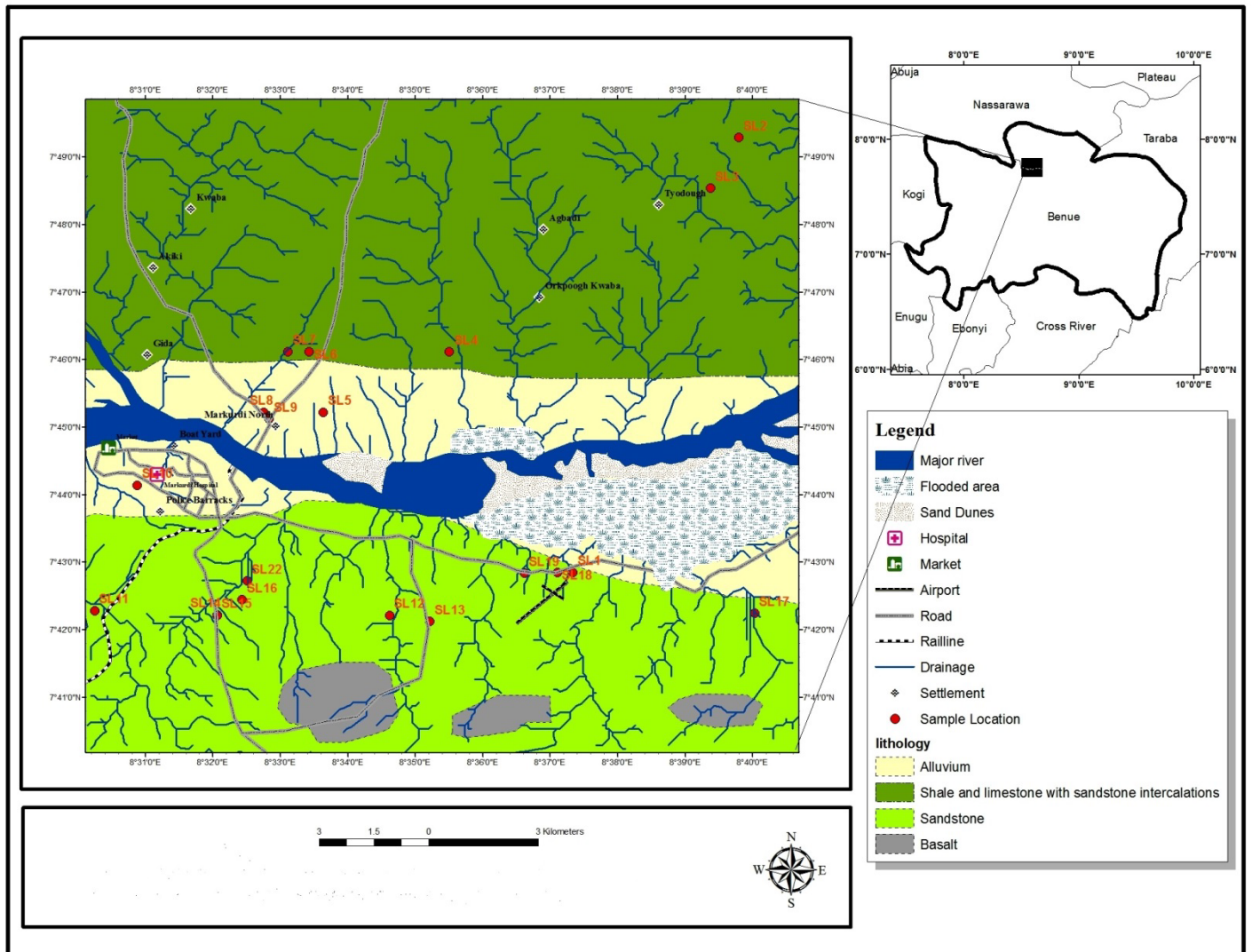
**Figure 1.** Map of Benue State showing the study area. Source: Adapted and modified from the administrative map of Benue State (2012).

(transitional) beds during the Late Albian-Early Cenomanian regression. This formation overlies the Asu River Group. Offodile (1976) estimated the thickness of the formation to be about 1000 m. The formation consists of flaggy, pale-colored medium to fine grained Sandstone with interbedded carbonaceous shale and clay (Offodile, 1976). The Sandstone beds, usually multi-layered appear highly porous and water yielding but the water from these aquiferous beds is contaminated by brines from the interbedded shales. The shale also confines the aquifer and present artesian to sub artesian situations (Offodile,

2002). A few boreholes drilled into this formation have produced good water yields, though often not potable due to the brine contamination.

The major flood plains of Benue State are those of Rivers Benue, Katsina Ala and other smaller rivers. Alluvial deposits, comprising an assortment of clays, sand, gravels and pebbles from these flood plains overlie the metamorphosed sediments and form the superficial geology.

The alluvium aquifer occurs along river and stream channels which are liable to seasonal flooding. It is the least extensive of all the aquifers. The thickness of the



**Figure 2.** Geological map of Makurdi metropolis and environs adapted from Nigeria Geological Survey Agency (2006) Geological and Mineral Resources map.

aquifer ranges from 2 to 15 m, the thickest occur along the Benue River while the least thickness is along the stream channels (Adanu, 1981). It suggested watertable (unconfined) aquifer condition for the alluvium aquifer. Adanu (1981) also reported porosity and permeability coefficient for this aquifer as 37.5% and about 0.26 m/day respectively. The permeability and porosity value favors effective recharge into the aquifer. Recharge into this aquifer is mainly direct from annual precipitation and indirect recharge occurring when the river character is influent, thus supplying water to the alluvium aquifer (Adanu, 1981).

## METHODOLOGY

Water samples were taken from four boreholes and 20 hand-dug wells at the peak of dry season (April, 2012) and stored in plastic

sample bottles. The sample points are located as shown in Figure 2. The sample bottles were washed twice with the water to be sampled and filled to overflow, sealed tightly to avoid contamination with atmospheric gases. 500 ml of the sample was acidified to pH of 2 with concentrated nitric acid and another 500 ml non-acidified. A portion of the sampled water was acidified to keep the heavy elements in solution while in storage. *In situ* measurement of some physical parameters such as temperature, pH and total dissolved solids (TDS) was done. Chemical analysis of water samples was carried out at the Center for Energy Research and Training (CERT), Department of Water Resources Engineering Laboratory and Multipurpose Science Research Laboratory all in Ahmadu Bello University Zaria. Three analytical techniques were employed in determining the concentration of the chemical parameters of interest. These includes: photometric method (Zn, Fe, Cu, Mn<sup>2+</sup>, Cl, NH<sub>3</sub> and NO<sub>3</sub>) using a Chemetric V – 2000 model multi – analyte photometer, atomic absorption spectrophotometry (Ca and Mg) titrimetric techniques (HCO<sub>3</sub>) and flame photometric method (Na and K). Values obtained were compared with maximum permissible limit set by the Standard Organization of Nigeria (SON, 2007) and

World Health Organization (WHO, 2011) to evaluate its suitability for drinking and domestic purpose.

The analytical data obtained were processed with aquachem 4.0 software for geochemical and statistical analysis. This software was used to plot Piper and Wilcox diagrams, deduce possible source of some chemical parameters and obtain correlation coefficient (Table 2) showing the relationship between the measured parameters. Basic statistical parameters such as minimum, maximum, mean, standard deviation and averages were also computed using aquachem 4.0 version software (Table 3).

Sodium adsorption ratio (SAR), percentage sodium (Na%) and bicarbonate hazard were used to evaluate the suitability of water for irrigation purpose. These parameters were determined using Equations 1, 2 and 3 respectively. Values obtained were compared with the classification of groundwater (Table 4).

## RESULTS AND DISCUSSION

### Physico-chemical parameters of groundwater

A summary of the physico-chemical analysis of the groundwater samples is presented in Table 1. pH values ranges from 2.90 to 7.26 with an average of 4.94 indicating acidic to slightly basic type of water. Only third (12.5%) of the 24 samples have values within the Standard Organization of Nigeria (2007) permissible range of 6.50 to 8.50 indicating that groundwater in most part of the study area is acidic. Total dissolved solids (TDS) ranges from 90 to 520 mg/l in boreholes and from 90 to 1250 mg/l in hand dug wells with an average of 489.55 mg/l. Chloride concentration ranges from 0.00 to 13.11 mg/l with an average of 2.92 mg/l. These values are far below the SON (2007) maximum permissible limit of 250.00 mg/l. No health-based guideline value is proposed for chloride concentration in drinking-water. Nitrate concentration ranges from 0.53 to 196.00 mg/l with an average of 42.61 mg/l. Four (16.7%) of the samples, SL7 and SL8 from North Bank, SL10 and SL11 from Wadata and George's quarters respectively have elevated concentrations of 107, 196, 96 and 117 mg/l, respectively above the maximum permissible limit of 50 mg/l (Table 1). Elevated nitrate concentration in groundwater has resulted from agricultural activities (for example, excess application of nitrogenous fertilizers and manures), from waste water disposal and oxidation of nitrogenous waste products in human and animal excreta. Results show a range of 0.34 to 3.20 mg/l with an average of 1.06 mg/l for ammonia concentration in groundwater within Makurdi metropolis (Table 1).

Sulphate concentration in groundwater within the study area ranges from 5.00 to 500.00 mg/l with an average of 28.25 mg/l. Only two (4.5%) of the samples analyzed had sulphate concentration above SON (2007) maximum permissible limit of 100 mg/l. Sulphate in groundwater within the study area as deduced from the aquachem software is from pyrite oxidation. Other sources of sulphate in groundwater includes; atmospheric precipitation and from the solution of sulphate minerals in sedimentary rocks (Davis and Dewiest, 1966). Most part

of the study area (about 95.5%) contains groundwater considered safe with respect to its sodium concentration. One location however, SL 8 at North Bank has elevated sulphate concentration (150 mg/l) and is therefore unsafe for drinking and domestic use. Sodium concentration ranges from 10.70 to 36 mg/l with an average of 17.24 mg/l. All samples analyzed had concentrations below SON (2007) maximum permissible limit of 200 mg/l. The source of sodium in groundwater in the study area has been traced to weathering of albite and ion exchange. Magnesium concentration in groundwater within the studied area ranges from 5.68 to 74.20 mg/l with an average of 23.32 mg/l. All the samples analyzed had concentration above SON (2007) permissible limit of 0.20 mg/l.

Guideline values have not been established for bicarbonate, potassium and calcium. Bicarbonate concentration in groundwater within the study area ranges from 90.90 to 1525.50 mg/l with an average of 555.97 mg/l and is derived from carbon dioxide in the atmosphere, carbon dioxide in the soil and dissolution of carbonate rocks. Potassium concentration ranges from about 1.80 to 94.50 mg/l with an average of 23.46 mg/l and calcium ranges from 2.78 mg/l to 144.74 mg/l with an average of 41.98 mg/l. Potassium results from weathering of orthoclase and microcline. The abundance of potassium and sodium is about the same but potassium is commonly less than one tenth of sodium in natural water because many potassium minerals have higher resistance to weathering (Davis and Dewiest, 1966). Calcium on the other hand, has resulted from the contact of water with sedimentary rocks of marine origin such as calcite, aragonite, dolomite and gypsum.

Concentration of iron ( $\text{Fe}^{3+}$ ) ranges from 0.00 to 0.47 mg/l in boreholes and 0.00 to 0.86 mg/l in hand dug wells with an average of 0.27 mg/l. 15 (62.5%) of the samples analyzed were within the SON (2007) permissible limit of 0.30 mg/l and nine (37.5%) samples had elevated iron concentration above the permissible limit. At concentrations above 0.30 mg/l, iron stains laundry and plumbing fixtures. There is usually no noticeable taste at iron concentrations below 0.30 mg/l, although turbidity and colour may develop (WHO, 2011). Sources of iron in groundwater could be from atmospheric absorption, leaching of the products of rock weathering especially pyrite, the use of galvanized hand pump (Idoko, 2010). Water from most part of the study area is safe for drinking and other domestic uses. Some parts of the study like Wurukum, Mu village, Kanshio, North bank and Airport however have iron in concentrations that make them unsafe for the uses earlier mentioned.

Manganese concentration ranges from 0.00 to 0.16 mg/l in boreholes and 0.00 to 2.43 mg/l in hand dug wells with an average of 0.48 mg/l. 18 (75%) of the samples show elevated manganese concentration above the SON (2007) maximum permissible limit of 0.20 mg/l while five (25%) of the samples had values below this limit.

**Table 1.** Results of water analysis from Makurdi metropolis and environs.

S/N	ID	TDS (mg/l)	PH	Temp (°C)	Fe <sup>3+</sup>	Cu <sup>2+</sup>	Mn <sup>2+</sup>	Zn <sup>2+</sup>	NH <sub>3</sub> <sup>-</sup>	Cl <sup>-</sup>	NO <sub>3</sub> <sup>-</sup>	Na <sup>+</sup>	K <sup>+</sup>	Ca <sup>2+</sup>	Mg <sup>2+</sup>	HCO <sub>3</sub> <sup>-</sup>	SO <sub>4</sub> <sup>2-</sup>
1	SL 1	130	5.65	29.5	0.47	0.11	2.43	0.22	0.54	0.97	0.53	11.6	2.5	3.18	22.1	90.9	5
2	SL 2	260	7	31.3	0.1	0.18	0.53	0	1.03	1.37	16	13.3	2.1	31.68	12.53	525.2	15
3	SL 3	400	3.1	30.3	0	0.11	0.39	0.02	1.39	0	15	12.3	3	42.33	36.49	858.5	40
4	SL 4	360	7.26	29.1	0.02	0.15	0.31	0.1	0.76	0.34	0.63	12.8	3	29.58	5.68	401.25	10
5	SL 5	320	4	28.6	0.27	0.09	0.36	0.1	0.82	1.75	32	16.7	18.6	8.16	74.2	232.3	25
6	SL 6	260	4.41	31.4	0.29	0.18	0.19	0.13	0.61	0	32	14	45.4	9.92	22.66	313.1	15
7	SL 7	850	2.24	32.2	0.38	0.01	0.28	0.09	0.86	9.28	107	20.9	51.1	41.5	9.71	700.65	5
8	SL 8	1230	4.34	30.4	0.27	1.93	0.26	0.12	3.2	13.11	150	36	2.99	94.5	7.43	1525.5	105
9	SL 9	90	4	30.5	0.47	0.11	0.53	0.16	0.53	1.39	16	10.5	4.7	18.45	10.99	171.7	15
10	SL 10	1190	5.82	29.4	0.2	0.87	0.49	0.12	2.8	11.29	96	35.5	66.5	49.59	9	550.30	6.5
11	SL 11	1250	6.44	29.9	0.25	0.9	0.54	0.09	0.34	10.76	117	36	64	36.25	15.43	450	50
12	SL 12	240	7.01	28.3	0	0.2	0.93	0.08	0.49	0	17	11.8	17.4	15.27	9.93	255	30
13	SL 13	330	5.8	31.2	0	0.14	1.28	0.06	0.89	0	33	10.7	8.3	4.39	7.09	200	25
14	SL 14	450	7.17	32.3	0.11	0.09	0.5	0.03	0.96	0.3	36	17.8	33.2	2.78	24.27	565.6	40
15	SL 15	170	4.33	32.3	0.35	0.29	0.66	0.11	1.11	0	26	10.4	7.3	32.86	38.59	181.8	15
16	SL 16	810	5.01	32.6	0.18	0.39	0.09	0.13	2.34	5.61	21.3	25.7	53.5	14.12	9.77	757.5	80
17	SL 17	180	4.18	29.6	0.86	0.28	0.24	0.16	0.5	0	38	12.1	1.8	25.19	21.86	131.3	5
18	SL 18	90	3.33	29.8	0.11	0.1	0	0.07	0.96	0	26	10.5	2.2	144.74	24.21	111.1	5
19	SL 19	520	5.91	31.7	0.37	0.27	0	0.11	0.83	0.39	18	20	2.5	119.71	22.98	505	20
20	SL 20	630	2.95	29.1	0.22	0.08	0	0.18	0.79	1.91	49	19.4	4.2	169.74	44.5	505	40
21	SL 21	520	5.88	30.4	0.58	0.35	0.13	0.07	0.61	0.88	16	13	2.3	10.63	39.54	767.6	10
22	SL 22	490	2.9	30.4	0.43	0.23	0	0.15	0.9	4.84	29	19.3	28	110.43	44.08	343.4	15
23	SL 23	130	4.18	28.1	0.13	0.13	0	0.06	0.37	1.09	28	11.7	3				
24	SL 24	520	5.88	30.4	0.66	0.97	1.29	0.14	1.58	0.98	21	13.1	2.8				
	Background	180			0	0.09	0	0.02	0.5	0		10.7	1.8	2.78	21.86	131.3	40
	SON MPL	500	6.5 -8.5		0.3	1	0.2	3		250	50	200			0.2		100

Units: mg/l except for pH and temperature (Temp): SON MPL: Standard organization of Nigeria Maximum permissible limit.

Concentration above 0.1 mg/l causes undesirable taste in beverages, stains sanitary wares and laundry (WHO, 2011) and neurological disorder (SON, 2007). Health-based value for manganese according to the World Health Organization is placed at 0.40 mg/l. Manganese

present in groundwater is usually absorbed from the atmosphere or leached from products of rock weathering.

Copper in water supply usually arises from the corrosive action of water leaching copper from copper pipes in buildings (WHO, 2011). This

corrosive action of water is often accelerated by high levels of dissolved oxygen in water. The analysis reveals concentration of 0.09 to 1.93 mg/l with an average of 0.31 mg/l for samples analyzed. At concentration above 5 mg/l copper imparts colour and an undesirable bitter taste to



**Table 2.** Correlation matrix for measured parameters

	pH	Na	Mg	Ca	Cl	K	SO <sub>4</sub> <sup>2-</sup>	TDS	Temp	Fe <sup>3+</sup>	Mn	Cu	Zn	NO <sub>3</sub> <sup>-</sup>	HCO <sub>3</sub> <sup>-</sup>	NH <sub>3</sub>
pH	1	0.05	-0.41	-0.42	-0.26	-0.03	-0.01	0.02	0.3	-0.33	0.27	0.09	-0.16	-0.18	0.1	-0.07
Na		1	-0.22	0.03	0.9	0.87	0.59	0.96	-0.16	-0.24	-0.19	0.78	0.1	0.81	0.78	0.63
Mg			1	0.26	-0.37	-0.32	-0.17	-0.25	-0.18	0.18	-0.1	-0.27	0.02	-0.25	-0.36	-0.25
Ca				1	-0.1	-0.24	-0.18	0.01	-0.13	-0.15	-0.24	-0.16	0.22	-0.07	-0.13	-0.09
Cl					1	0.93	0.51	0.9	0.02	-0.05	-0.17	0.77	-0.07	0.9	0.8	0.63
K						1	0.64	0.83	-0.05	-0.23	-0.26	0.74	-0.12	0.84	0.72	0.65
SO <sub>4</sub> <sup>2-</sup>							1	0.57	0.02	-0.23	-0.21	0.76	-0.01	0.64	0.58	0.65
TDS								1	0.15	-0.21	-0.25	0.74	0.01	0.82	0.88	0.61
Temp									1	-0.08	0.15	-0.06	-0.11	-0.12	-0.15	-0.17
Fe <sup>3+</sup>										1	0.09	-0.03	0.37	-0.07	-0.3	-0.31
Mn											1	-0.12	0.43	-0.2	-0.36	-0.29
Cu												1	0.12	0.83	0.71	0.71
Zn													1	0.01	-0.18	0.03
NO <sub>3</sub> <sup>-</sup>														1	0.73	0.56
HCO <sub>3</sub> <sup>-</sup>															1	0.71

**Table 3.** Statistical summary of measured parameters.

Parameter	Min	Max	Mean	St. Dev.	Dev. Coef
TDS (mg/l)	90	1250	489.545	362.931	74.136
pH	2.24	7.26	4.942	1.538	31.126
TEMP (°C)	28.6	32.6	30.571	1.194	3.906
Fe <sup>3+</sup> (mg/l)	0	0.86	0.27	0.213	79.152
Mn <sup>2+</sup> (mg/l)	0	2.43	0.477	0.549	115.096
Cu <sup>2+</sup> (mg/l)	0	1.93	0.307	0.433	140.963
Zn <sup>2+</sup> (mg/l)	0	0.22	0.099	0.057	57.532
Ca <sup>2+</sup> (mg/l)	2.78	169.74	46.136	48.969	106.139
K <sup>+</sup> (mg/l)	1.8	66.5	19.3	22.48	116.481
Mg <sup>2+</sup> (mg/l)	5.68	74.2	23.32	16.98	72.814
Na <sup>+</sup> (mg/l)	10.4	36	17.741	8.424	47.483
Cl <sup>-</sup> (mg/l)	0	13.11	2.918	4.262	146.068
HCO <sub>3</sub> <sup>-</sup> (mg/l)	90.9	858.5	409.973	232.618	56.74
SO <sub>4</sub> <sup>2-</sup> (mg/l)	5	105	26.205	25.481	97.24
NH <sub>3</sub> <sup>-</sup> (mg/l)	0.34	3.2	1.057	0.751	71.076
NO <sub>3</sub> <sup>-</sup> (mg/l)	0.53	150	40.521	39.799	98.218

Min: minimum, Max: maximum, St. Dev.: standard deviation, Dev. Coef: deviation coefficient.

water (WHO, 2011). Maximum permissible limit of copper concentration in water for drinking and domestic uses by SON (2007) is set at 1.00 mg/l; consumption of water with concentration above this value causes gastrointestinal disorder. All except one (SL 8 at North Bank) of the samples analyzed had concentration below the permissible limit. With an exception of the immediate area around SL 8 at North Bank, groundwater in Makurdi

metropolis is considered safe for drinking and domestic uses with respect to its copper concentration. All samples analyzed had zinc concentration below the SON (2007) permissible limit of 3.00 mg/l with concentration ranging from 0.00 to 0.18 mg/l with an average of 0.09 mg/l.

### Statistical analysis

The correlation coefficient reveals some relevant hydrochemical relationships, the content of TDS have high positive correlation with Na<sup>+</sup>, Cl<sup>-</sup>, K<sup>+</sup> and SO<sub>4</sub><sup>2-</sup> with correlation coefficients of 0.96, 0.90, 0.62 and 0.56 respectively (Table 2). This positive correlation indicates that the ions are derived from the same source. In a similar way, there exists positive correlation between Cl<sup>-</sup> – Na<sup>+</sup> (0.90), K<sup>+</sup> – Na<sup>+</sup> (0.63), K<sup>+</sup> – Cl<sup>-</sup> (0.63), NO<sub>3</sub> – NH<sub>3</sub> (0.5), NO<sub>3</sub> – Cl (0.92) and Na – Cl (0.90). The high positive correlation (0.90) between Na<sup>+</sup> and Cl<sup>-</sup> may represent influence from salty water.

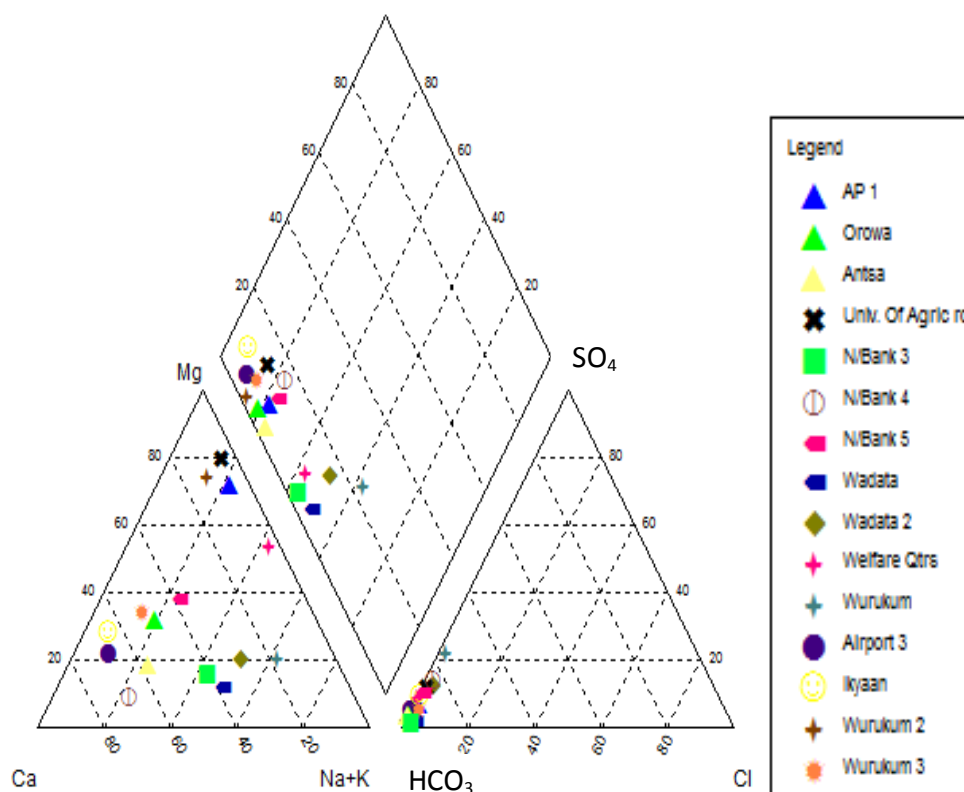
On the other hand, there are negative relationships between Mg – Na, Mg – K, K – Ca, SO<sub>4</sub> – Mg and HCO<sub>3</sub><sup>-</sup> – Mg. These relationships could indicate ion exchange process between the groundwater and soil minerals.

### Hydrochemical facies

From the Piper plot (Figure 3), an evaluation of the hydrochemistry of groundwater in Makurdi metropolis was done. The groundwater samples fall in the fields of Mg – Na – HCO<sub>3</sub>, Mg-K-HCO<sub>3</sub>, K – HCO<sub>3</sub> – SO<sub>4</sub>, Mg-Ca-HCO<sub>3</sub>, Mg-HCO<sub>3</sub> and Ca - Mg - HCO<sub>3</sub> in order of increasing dominance.

**Table 4.** Calculated values of bicarbonate hazard, percentage sodium and sodium adsorption ratio for groundwater in Makurdi metropolis and environs.

Location description	Sample ID	Bicarbonate hazard (meq/l)	SAR	Na%	EC (μS/cm)
Air Port 1	SL 1	0	0.51	22.45	91
Orowa Village	SL 2	5.99	0.51	17.26	182
Miande Akpu Village	SL 3	8.96	0.33	7.18	280
Antsa Village	SL 4	10.31	0.56	24.89	252
University Of Agriculture Road	SL 5	0	0.40	11.38	224
North Bank 2	SL 6	2.77	0.56	41.69	182
North Bank 3	SL 7	12.52	0.76	40.62	595
North Bank 4	SL 8	24.24	2.54	104.49	861
North Bank 5	SL 9	0.99	0.48	24.92	63
Wadata	SL 10	17.98	1.22	45.18	833
Wadata 2	SL 11	11.82	1.26	46.15	875
Georges Qtrs	SL 12	3.39	0.58	40.31	168
Nyon Village	SL 13	6.65	0.73	63.99	231
Welfare Qtrs	SL 14	7.14	0.75	42.53	315
Kanshio	SL 15	0	0.29	8.77	119
Wurukum	SL 16	10.91	1.29	66.48	567
Mu Village	SL 17	0	0.43	13.00	126
Airport 2	SL 18	0	0.21	2.77	63
Airport 3	SL 19	0.41	0.44	5.71	364
Ikyaan Village	SL 20	0	0.34	3.44	441
Wurukum 2	SL 21	8.79	0.41	10.66	364
Wurukum 3	SL 22	0	0.39	10.37	343



**Figure 3.** Piper diagram of groundwater in Makurdi metropolis and environs.

**Table 5.** Classification of groundwater based on Na%, SAR and bicarbonate hazard (source: Tabue et al., 2012).

Parameters	Range (meq/l)	Class
Na%	>200	Above max permissible limit
	20 – 40	Good
	<20	Excellent
SAR	20 - 40	Good
	40 - 60	Permissible
	60 - 80	Doubtful
	>80	Unsuitable
Bicarbonate hazard	0.00 – 1.25	Safe
	1.25 – 2.50	Marginal
	>2.50	Unsuitable

### Suitability of groundwater for irrigational purposes

The quality of water used for irrigation purpose is of great importance for crop productivity, soil maintenance and environmental protection (Tabue et al., 2012). The quality of groundwater as earlier explained is influenced by the mineral composition of the aquifers within which water is stored as well as the residence time in these aquifers.

### Percent sodium (Na%)

The percentage sodium was calculated using the expression:

$$\text{Na\%} = \left( \frac{\text{Na}^+ + \text{K}^+}{\text{Ca}^{2+} + \text{Mg}^{2+} + \text{Na}^+ + \text{K}^+} \right) \times 100 \quad (1)$$

Within the study area, Na% varies from 3.44 to 104.50% (Table 4) and are less than the maximum allowable limit of 200% (Table 5). Three (14 %) of the samples fall within the class of 20 to 40 Na% and are considered good for irrigation. Nine samples (41 %) have percentage sodium values above the 20 to 40% class but are still below the maximum permissible limit of 200. Ten (45%) have Na% less than 20% and are considered excellent for irrigation (Table 5).

Higher Na% observed in groundwater from nine locations which constitutes 41% of the study area indicates the dominance of ion exchange and weathering from lithological units of the study area (Tabue et al., 2012). Groundwater with relatively high Na% values above 40 occurs around North bank, Wadata, George's quarters, Nyon, welfare quarters and Wurukum. When the concentration of sodium is high in water, sodium tends to be absorbed by clay particles displacing magnesium and calcium. This exchange of sodium for calcium and magnesium reduces soil permeability and results in soil

with poor internal drainage. A larger proportion (59 %) of groundwater within the study area is considered safe for irrigation.

### Sodium adsorption ratio (SAR)

This was calculated using the expression (SAR) = .....

(2)  
SAR for samples within the study area varies from 0.21 to 2.54. The groundwater according to the classification in Table 4 is of excellent quality with respect to sodium adsorption ratio. If water used for irrigation has high Na<sup>+</sup> and low Ca<sup>2+</sup>, the ion exchange complex may become saturated with Na<sup>+</sup> which destroys the soil structure due to dispersion of clay particles and reduces plant growth (Tabue et al., 2012). High Na<sup>+</sup> and low Ca<sup>2+</sup> in water used for irrigation results in ion exchange complex which becomes saturated with Na<sup>+</sup> as a result of clay particle dispersion. This causes the destruction of the soil structure and consequently reduces plant growth.

The Wilcox diagram (Figure 4) also shows that all samples analyzed fall within the S1C1, S1C2 and S1C3 regions. This indicates water of good quality for irrigation.

High Na<sup>+</sup> and low Ca<sup>2+</sup> in water used for irrigation results in ion exchange complex which becomes saturated with Na<sup>+</sup> as a result of clay particle dispersion. This causes the destruction of the soil structure and consequently reduces plant growth.

### Bicarbonate hazard

Bicarbonate hazard means excess of bicarbonate over calcium and magnesium, all expressed in milliequivalent per liter. Water with bicarbonate hazard greater than 1.25 meq/l should not be used for irrigation except on very sandy, highly permeable soils or with some soil chemical amendments such as the application of gypsum. Bicarbonate hazard was computed using the expression

$$\text{HCO}_3^- - (\text{Ca}^{2+} + \text{Mg}^{2+}) \quad (3)$$

Only nine (41%) of the samples analyzed (SL 1, SL 5, SL 9, SL 15, SL 18, SL 19 and SL 20) fall within the class of samples considered safe (0.00 to 1.25 meq/l) for irrigation in terms of bicarbonate hazard. Groundwater from other locations should not be used for irrigation purpose except on soils that are sandy, permeable or with some chemical amendments as they are considered unsuitable (Table 4).

### Conclusions

Groundwater is of immense importance to both rural and urban dwellers of developing nations. The groundwater of the study area is acidic to slightly basic in nature.

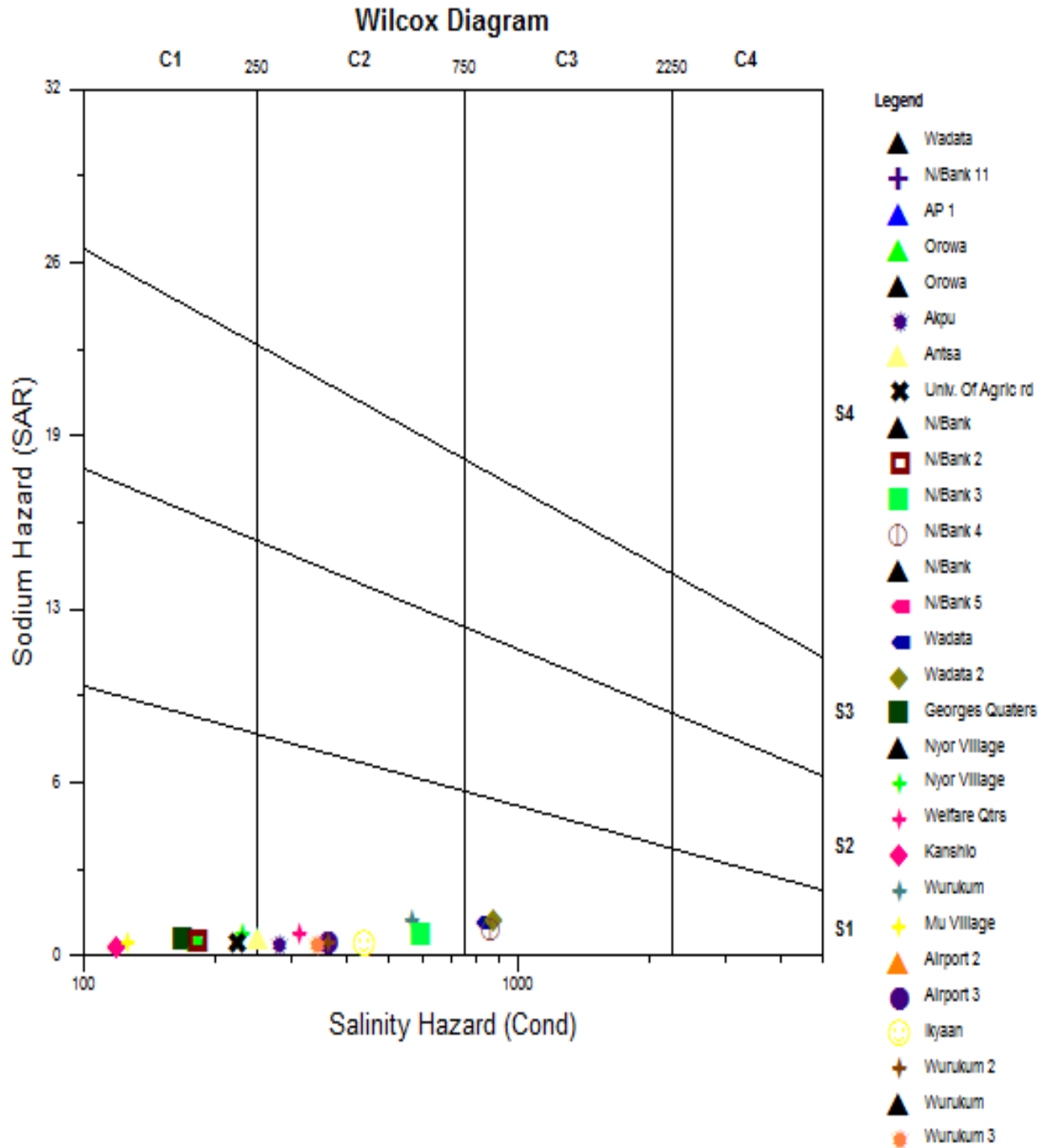


Figure 4. Wilcox diagram of groundwater in Makurdi metropolis and environs.

Groundwater in Makurdi metropolis and environs has been evaluated for its chemical composition and suitability for drinking and irrigation purposes.

The abundance of chemical concentrations in groundwater within the study area is in order of  $Ca > Mg > Na > K$  for the cations and  $HCO_3^- > SO_4^{2-} > NO_3^- > Cl^-$  for the

anions. Groundwater in some parts of the study area have elevated TDS, magnesium, sulphate, nitrate, copper, manganese and iron concentrations above the SON (2007) maximum permissible limit for drinking water and considered unsafe for drinking with respect to these parameters (Figure 5). The acidic nature of groundwater

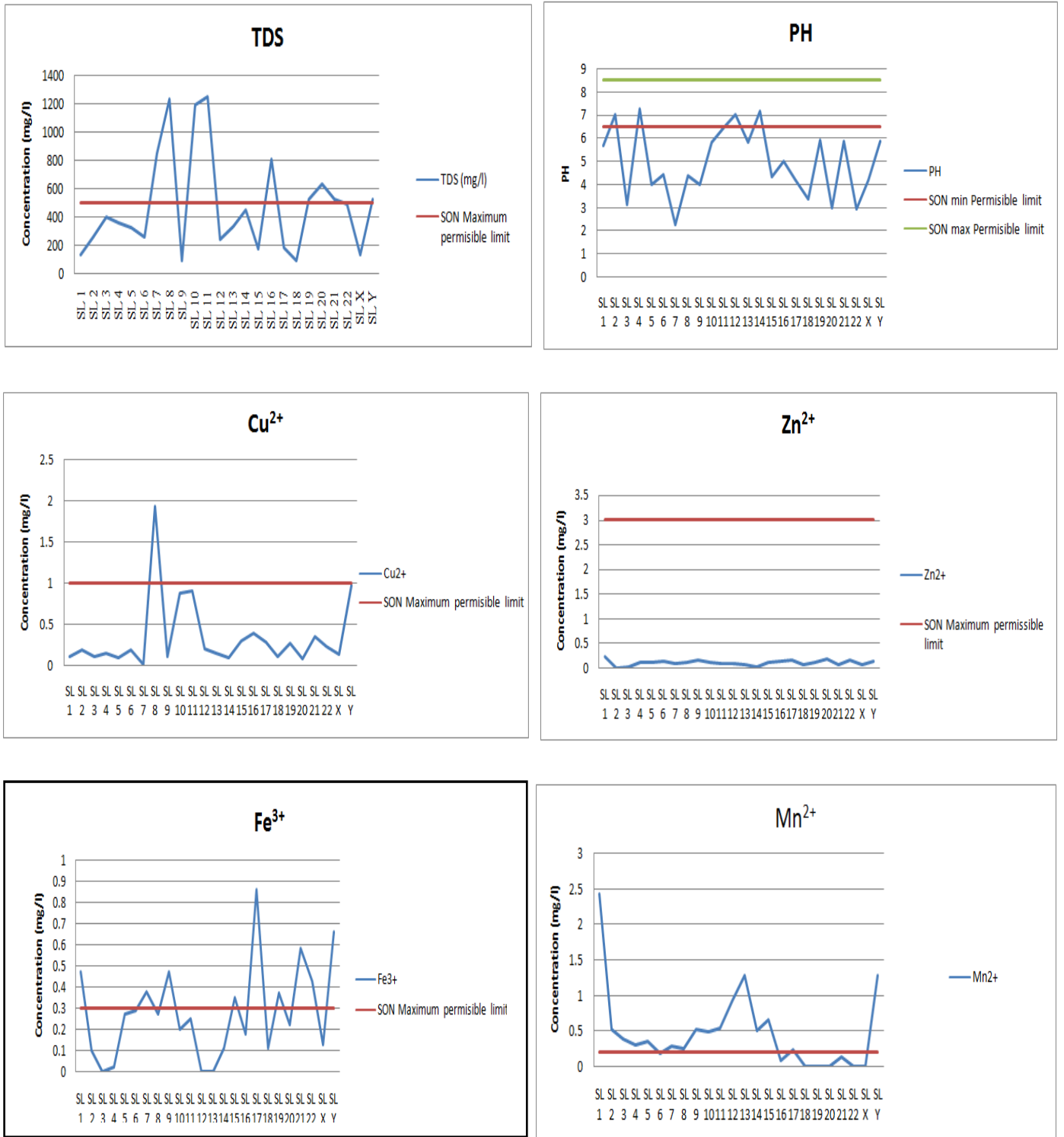


Figure 5. Plots of concentrations of measured parameters and Standard Organization of Nigeria's 2007 permissible limits.

in the study area has also impaired its quality. Northbank and Wadata areas are identified to be areas where groundwater is polluted the most and this is attributed to the poor sanitary conditions in these areas.

Groundwater within the study area is safe for irrigation with respect to its sodium adsorption ratio but a large portion of it has high percentage sodium and bicarbonate hazard and should not be used for irrigation except on

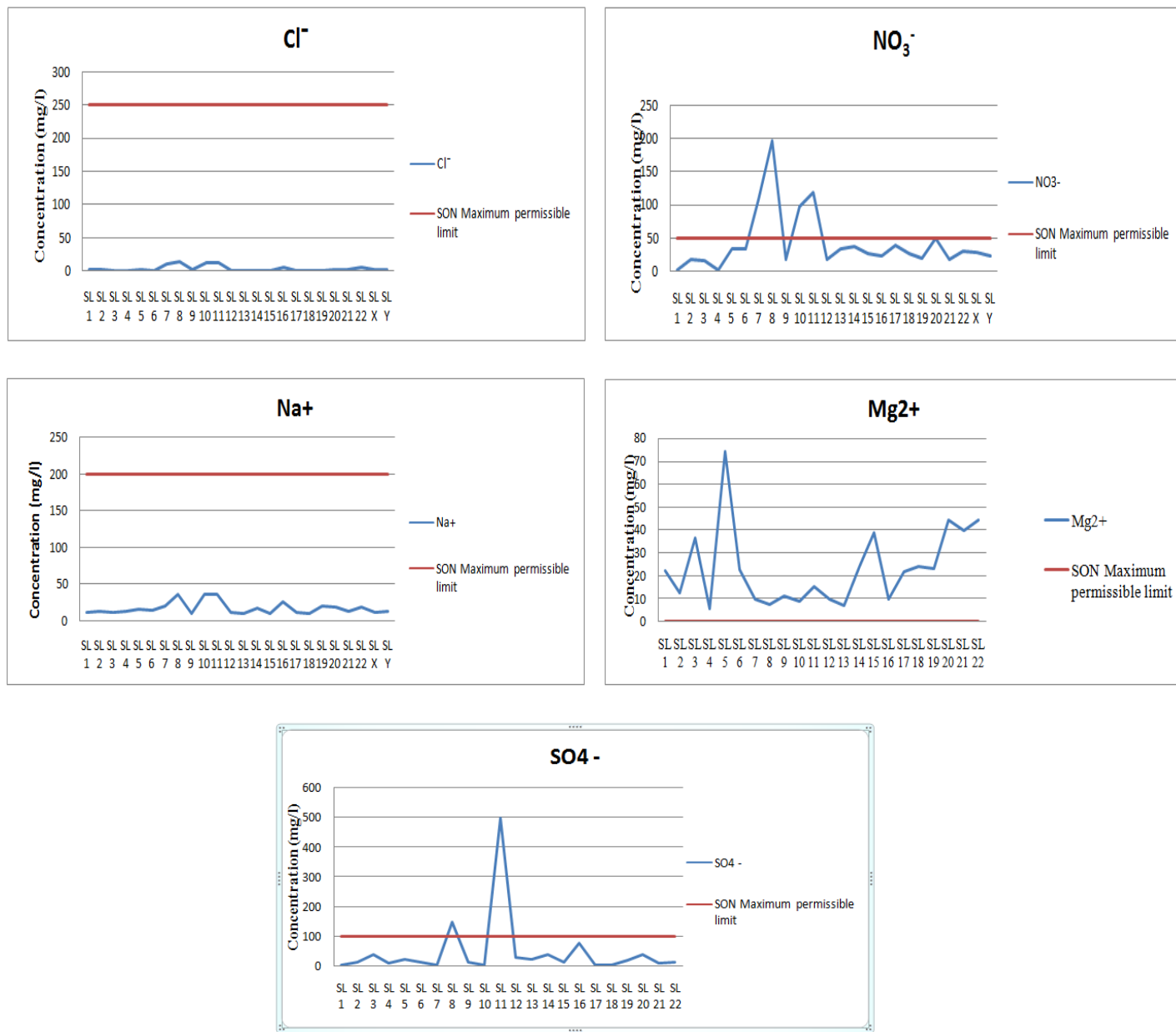


Figure 5. Contd.

very porous and permeable soils or when used with some chemical soil amendments.

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