World Journal of Advanced Research and Reviews

eISSN: 2581-9615 CODEN (USA): WJARAI

Cross Ref DOI: 10.30574/wjarr

Journal homepage: https://wjarr.com/

(Review Article)

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Valorization of electromechanical waste in biodigesters and Pyrolyzers for sustainable management of organic waste

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World Journal of Advanced Research and Reviews, 2026, 30(02), 552-558

Publication history: Received on 28 March 2026; revised on 06 May 2026; accepted on 08 May 2026

Article DOI: https://doi.org/10.30574/wjarr.2026.30.2.1215

Abstract

The management of electromechanical waste in Niger represents a major challenge for environmental protection and socio-economic development. This innovative work proposes to utilize readily available electromechanical waste to construct multifunctional pyrolyzers and pyrolyzers, as well as hybrid systems for combined heat and power (CHP) generation. The biodigesters and pyrolyzers will be used to produce bioenergy (biogas, green charcoal) and biofertilizers (compost and biochar) from organic waste and invasive plant species. This work will enable effective waste management in general, which currently poses a challenge for local authorities, while simultaneously developing the renewable energy and biofertilizer production sectors, contributing to pollution reduction, and improving the living conditions of local populations.This project is part of a broader energy transition and land restoration initiative in Niger, combining technological innovation, social impact, and environmental responsibility. Through the construction and installation of biogas digesters and pyrolyzers adapted to the local context, each community or household will have the capacity to harness the energy and fertilizing potential of organic waste and proliferating plants. The biogas produced will be used to promote green cooking, a more ecological alternative to traditional fuels. Furthermore, this renewable energy will also be used for electricity generation, meeting the energy needs of communities and families while reducing their dependence on non-renewable energy sources. The biofertilizers (digestates and biochars) resulting from the operation of the innovative biodigesters and pyrolyzers will be used to fertilize cultivated and degraded land.This article combines proven technological solutions with participatory approaches, engaging local communities in the process of collecting and managing electromechanical and organic waste. It aims to reduce greenhouse gas emissions, create sustainable jobs, and strengthen the region's resilience to energy and climate challenges.

Expected results include improved air quality, reduced greenhouse gas (GHG) emissions, and increased awareness of best practices in urban waste management.

Keywords: Art; Electromechanical waste; Pyrolyzers; Pyrolyzers

1. Introduction

During the 21st century, sub-Saharan Africa is one of the regions of the world experiencing rapid transformation due to its population growth and rampant urbanization. Consequently, waste production by African urban centers has increased considerably in recent decades (Mebratu D. and Mbandi A., 2022). In sub-Saharan Africa, this waste production is estimated at approximately 9% of global production (Fig. 1a), or 180 million tons. Around two-thirds of this waste ends up in landfills and open dumps, thus polluting the local environment and impacting the global climate

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(Kaza et al., 2018). Qualitatively, this waste is distributed as shown in Figure 1b: Organic biomass (43% food and green waste, 10% paper and cardboard, and 1% wood or timber). Plastics account for 8.6%, metals 5%, glass 3%, and other materials 30%, largely originating from electromechanical waste. This breakdown shows that organic biomass represents approximately 54% of waste in Sub-Saharan Africa. Therefore, urban waste management is a major challenge, particularly in densely populated urban areas with significant socio-economic activity.

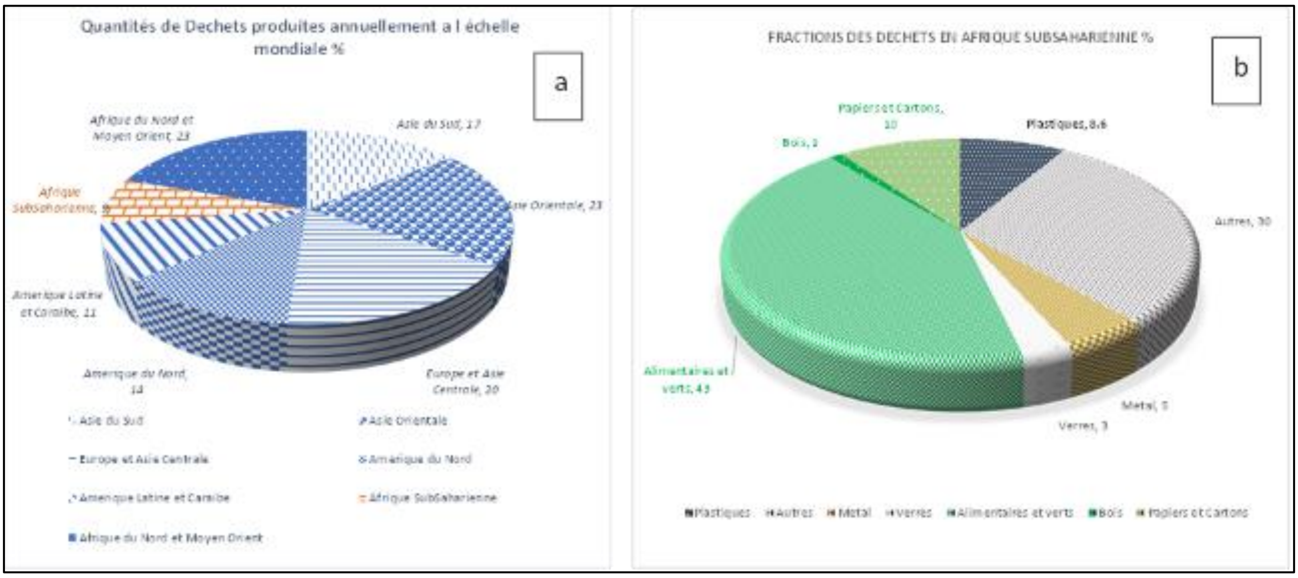

Figure 1 (a) Quantitative distribution of global urban waste and (b) its composition in sub-Saharan Africa (Kaza et al., 2018)

1.1. State of the Art

According to projections by the United Nations (Tabutin D, 1991), the African population will increase from 220 million inhabitants in 1950 to approximately 1.5 billion in 2025. This growth is even more rapid in sub-Saharan countries. Consequently, energy needs will double or more. How can we meet these energy needs while simultaneously reducing greenhouse gas emissions? Energy production from fossil fuels generates more nitrous oxide (N2O), methane (CH4), carbon dioxide (CO2), and other greenhouse gases, which exacerbate global warming. The already felt consequences of this warming could become even more devastating and costly (IPPC 2023) if no action is taken. Indeed, according to Crippa, M et al., 2023, in 2022, the majority of GHG emissions consisted of fossil CO2, representing 71.6% of total emissions, while CH4 accounted for 21% of the total, N2O 4.8%, and fluorinated gases 2.6%. Global fossil CO2 emissions have increased by more than 70% since 1990. The increase in CH4 and N2O emissions has followed a somewhat slower pace: CH4 has creased by 32.4% and N2O by 36.5% between 1990 and 2022, while fluorinated gases quadrupled during the same period.

Municipal landfills cause serious environmental problems due to the organic and inorganic pollutants in leachate plumes (UN Environment Programme 2018, Lee et al., 2020). The lack of a waste management system leads to severe environmental pollution, which in turn has detrimental effects on human health and the environment (Kafando et al., 2013). The composition of leachate, in terms of chemical and microbiological materials, varies according to the different types of landfill sites and depends on the characteristics of the solid waste, the age of the landfill site, the climate, environmental conditions, the landfill site's operating method, and the decomposition mechanism of the organic matter (Qin et al., 2016; Puig et al., 2011). Generally, waste decomposition processes by bacteria in landfill sites involve four stages: (i) hydrolysis, (ii) acid fermentation, (iii) acetogenesis and methanogenesis, and (iv) a settlement phase. This entire system is dynamic, and each phase creates an environment suitable for the previous stage, leading directly to the production of gas and leachate. The first phase of decomposition of The decomposition of waste depends on the amount of oxygen in the organic matter, and this phase continues until the available oxygen is depleted. This phase is followed by reactions such as oxidation, hydrolysis, and anaerobic acidification. In particular, the third phase, acetogenesis and methanogenesis, results in a decrease in acetic acid (CH3COOH) and determines the production of methane (CH4) and carbon dioxide (CO2). CH4 and CO2 are the main landfill gases, and their formation is influenced by bacterial decomposition, waste composition, organic matter availability, moisture content, pH, temperature, and the chemical reactions that can occur at landfill sites (Medeiros et al., 2018; Varjani et al., 2018). It is essential to study the environmental risks associated with landfill leachate that ends up in groundwater and the composition of the atmosphere. Furthermore, the behavior of certain heavy metals (e.g., Pb, Mo, Cr, etc.) during the thermal treatment of municipal solid waste is a serious environmental concern. The study of environmental isotopes can contribute to better waste management and the development of safe energy production processes. Isotope analyses can identify potential sources of gaseous pollutants (GHGs) and harmful chemical elements resulting from the storage and combustion of organic and electromechanical waste. Niger is not immune to this major challenge of the century. Indeed, municipal authorities remain without a solution to this dilemma. The country is experiencing rapid population growth and extensive urbanization. The sanitation of its cities, still largely unmechanized compared to developed countries, results in disastrous urban conditions. A particularly distressing example is the green belt, which has become a veritable open-air dump in the heart of Niger's capital (Fig. 2). Municipalities responsible for waste management are overwhelmed, and the collection rate for urban solid waste ranges from 15% to 40% (Niger Ministry of the Environment). The consequences for the health of populations living near these landfill sites are numerous. These populations ingest and inhale toxic substances daily from storage and incineration sites, which are generally open-air. These gases and fine particles released into the air cause many illnesses, such as lung and heart problems, cancer, infertility, premature births or even undercoat births, cognitive development problems, and premature deaths. Furthermore, these municipal dumps constitute significant sources of greenhouse gases such as CH_4 (20%) and CO_2 (11%). A study conducted by Tankari Dan-Badjo et al. (2014) at various sites in Niamey (Fig. 3) clearly demonstrates that areas with high levels of soil contamination are located near landfills containing all types of waste. High levels of heavy metals, such as cadmium (Cd), copper (Cu), lead (Pb), and zinc (Zn), exceeding international standards, were found in the Gounti Yena Valley (Dan-Badjo et al., 2014). According to the authors, the adverse effects on human health at concentrations above permitted limits are a cause for concern regarding their transfer into the food chain. Indeed, some plant species (lettuce, tomatoes, and cabbage) grown near landfill sites show high levels of heavy metals that can cause serious health problems. According to the United Nations International Emergency Children's Fund, approximately 56% of the Nigerien population has access to a source of drinking water, with a 7% increase in the supply of services between 2012 and 2015. Only 13% of the population has access to basic sanitation services. Open defecation is practiced by more than 71% of the population, with serious consequences for health, nutrition, education, and economic development. Recent studies in the Maradi and Zinder regions have also reported cases of groundwater contamination by fluorides from urban waste or lithological sources (e.g., Zeinabou M et al., 2022; Gourouza A et al., 2019; Sandao et al., 2019). Fluoride is beneficial for good dental health. However, ingesting high concentrations can cause gastrointestinal problems, nausea, vomiting, headaches, and serious mental health issues, including lethargy and even dementia. Excess fluoride can also cause bone diseases such as osteoporosis and osteosclerosis (genu valgum due to fluoride toxicity). Some of these diseases can occur even if the individual has ingested doses as low as 0.1 to 0.3 mg/kg, which is 50 times less than the probable lethal dose (PLD) of 5 mg/kg. In the Maradi region, prolonged consumption of these waters has had serious health consequences for some populations (Denise Williams et al., 2002).

Figure 2 Open-air waste storage in the green belt in downtown Niamey (Photo MOUNKAILA Mohamed Niamey 2024)

Thus, approximately five thousand (5,000) children suffered from dental fluorosis, five hundred (500) of whom developed skeletal fluorosis. This abnormal presence of fluoride ions has rendered some water sources unfit for consumption in the Maradi and Zinder regions. This significantly reduces the already insufficient water resources in these regions, particularly in Zinder. It should also be noted that cases of bacteriological pollution have been observed

(Chippaux et al., 2002). Indeed, the author indicates that the shallow aquifer accessible through wells in the city of Niamey contains coliform bacteria and fecal streptococci, rendering this water unfit for consumption. The deep aquifer, which supplies the boreholes, is also chemically polluted (oxidizable nitrogen) and bacteriologically polluted (fecal streptococci), but to a lesser degree. Fecal pollution increases after the rainy season due to runoff carrying waste into surface water and seeping into groundwater. This is a consequence of inadequate urban sanitation and poor waste management. The risks are now even greater with increasing population density, the use of borehole water in urban areas, and the uncontrolled sale of bottled water.

1.2. Issues: The storage and combustion of organic and electromechanical waste: a daily national challenge

Niger's subsoil is rich in all energy sources, including fossil hydrocarbons (oil, gas) and rare metals (uranium (U), cobalt (Co), lithium (Li)). It also possesses all renewable energy sources: sun, wind, rivers, and thermal springs usable for electricity generation. Paradoxically, despite these natural advantages, the country's electricity coverage was only 15% in 2020 (Ministry of Energy – Niger Electrification Program). According to the same source, this is the lowest rate in West Africa. In rural areas, where over 80% of the population lives, electricity coverage is estimated at only 5%. Another major energy challenge for the country is its heavy reliance on energy imports. Indeed, the negative impacts of this dependence in Nigeria have been felt by all segments of society since July 2023. A National Electricity Access Strategy (NEAS) has been implemented. Since 2018, within the framework of the National Electricity Policy (DPNE) adopted by the Government, this project has been contributing innovative techniques to the implementation of this strategy and goes far beyond it, as it encompasses environmental protection by including invasive biomass as an energy source and electromechanical waste as a source of raw materials through the design of biodigesters, pyrolyzers, and hybrid generators.

Indeed, invasive biomass and urban waste (organic and electromechanical) represent significant materials for the construction of components and sources of renewable energy production. In recent years, green energy has received particular attention as a renewable and sustainable alternative to traditional fossil fuels. In rural areas of Niger, energy supply depends either on stand-alone internal combustion engine systems, photovoltaic or thermal solar networks, or, more rarely, on connection to a national electricity grid. In the case of autonomous systems using fossil fuels, the fuel supply is irregular in both quantity and quality (shortages of petroleum products, problems transporting fuel to rural areas, final cost of energy, etc.) Due to their sporadic nature and low power output, photovoltaic installations cannot provide an energy service compatible with non-industrial or industrial activities when the power requirement exceeds 100 kilowatts. As for the national electricity grid, unreliable and prone to recurring power outages, it prioritizes capital cities and large urban areas. Furthermore, the price per kWh is very high for the 80% of the population living in rural areas. Continuous access to energy, in sufficient quantity and at a reasonable price, is essential for economic and social development. Expanding electrical infrastructure, strengthening the grid, and utilizing endogenous renewable energy resources such as biological and urban waste could be among the priorities of the national development strategy. Indeed, more than 90% of Nigerien households use wood as fuel for cooking. Access to modern cooking fuels and other forms of modern energy remains very limited. Bioenergy is a key energy option for a wide range of applications and will be an important source of energy for the country's development in the foreseeable future. The overexploitation of biomass has exacerbated negative environmental impacts, leading to ongoing soil degradation, a decline in biodiversity, and ultimately, desertification. This deforestation process exposes soils to severe degradation from wind and runoff. Furthermore, the use of traditional biomass for cooking has amplified health and mortality rates due to the resulting air pollution. These activities lead to an increase in greenhouse gas (GHG) emissions and consequently contribute inevitably to global warming (IPPC 2001). The graph (Fig. 3a) shows an increasing trend in GHG emissions from 1990 to 2022 by sector in Niger (JRC EU 2023). The figure shows that the highest emitting sectors are agriculture and waste. According to the same source, the distribution of the main greenhouse gases emitted (Fig. 3b) shows a clear dominance of methane (69.6%), followed by nitrous oxide (23.1%) and carbon dioxide (6.1%). Fluorine gases represent 1.3%. This high methane level is encouraging for biogas production through the methanization of agricultural residues and urban waste.

This trend is indeed closely correlated with population growth. In 2014, Niger had a population of 18,389,164 (according to INS-Niger), with urban and rural populations of 2,982,539 and 15,406,625 respectively (CNDDE 2020). An estimate based on a 2008 Oxfam-Québec study, updated in 2013, for the city of Niamey indicates that approximately 15,488 tonnes of household solid waste are produced daily, resulting in a tonnage of 5,653,230 tonnes per year. Daily production per capita across the country was estimated at 0.182 kg/capita/day in 2014. Municipal solid waste is produced in large quantities and typically contains a high proportion of putrescible (organic) components, such as food, kitchen waste, and garden waste. Organic waste constitutes 60 to 70% of municipal solid waste (CNDDE, 2020). Faced with increasing waste production in urban centers, municipalities' capacity to adapt has been overwhelmed. Public waste management services have been unable to establish the necessary conditions for the proper development of the sector. Consequently, the gap between waste production and collection has widened. This has resulted in a proliferation of illegal dumpsites, with serious consequences for the environment and the economy. Thus, there is enormous potential for biofuel and biogas production for various uses, such as electricity generation and composting, which is necessary for restoring degraded land. Technologies utilizing agricultural biomass residues and urban waste can be developed to produce mini power plants, biogas, biofuel, and improved cookstoves as substitutes for traditional stoves. Bioenergy, in the form of bioethanol and biodiesel, could serve as a substitute or complement to petroleum products in the transportation sector. Among the various advantages of bioenergy are the reduction of greenhouse gas emissions, the creation of rural livelihoods, foreign exchange savings, and reduced dependence on fossil fuels (ClimDev-Afrique, 2014). Indeed, the use of biomass as an energy source, the incineration of urban solid waste, and wastewater treatment release enormous quantities of carbon dioxide and other greenhouse gases. The emissions balance in the waste sector is estimated at 945,564 GgCO2eq distributed as follows: (i) CO2: 1,131 GgCO2; (ii) and (iii) CH4: 133,575 GgCO2eq; - N2O: 810,858 GgCO2eq (CNDDE, 2020) The CO2 fraction is often ignored as not contributing to the net increase in long-term atmospheric concentrations. However, this neutrality depends on the growth of plant biomass, which recaptures the equivalent over a short time horizon; otherwise, the balance between carbon in the atmosphere and the biosphere is altered. In the natural world, every unit of greenhouse gas (GHG) emitted has an impact that must be considered, and given the strict carbon budget constraints, this must be taken into account in the assessment. Bioenergy systems reduce GHG emissions by replacing an existing, relatively carbon-intensive fuel with a biomass feedstock that has generated fewer GHG emissions throughout its supply chain. Verifying GHG reductions therefore requires considering the entire supply chain and an awareness of the broader impacts of bioenergy implementation. Techniques such as life cycle assessment (LCA) can be used to verify this (Francesco, 2009).

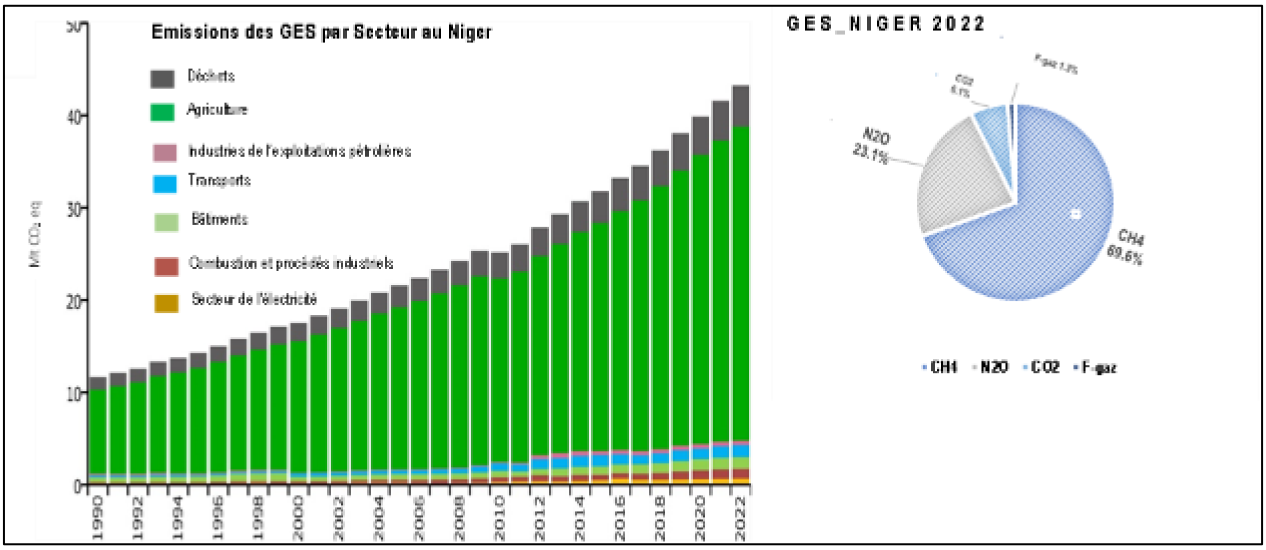

Figure 3 (a) Evolution of GHG emissions by sector of activity in Niger from 1999 to 2022

Figure 4a shows an exponential increase in GHGs in the agriculture and waste sectors. A significant increase can be expected in the oil and gas industry and processes, buildings, and transport sectors. Figure 4b shows the distribution of the main GHGs and fluorinated gases. It shows that 69.6% of these gases are methane (CH4) and 23.1% are nitrogen (N2O). Source: Emissions Database for Global Atmospheric Research (EDGAR) – European Commission. If humanity is to mitigate the effects of climate change, it must transition to an energy economy primarily based on renewable or carbon-free sources. To understand the challenge posed by waste storage, one must recall the famous apocryphal quote attributed to the alchemist Antoine Lavoisier, "Nothing is lost, nothing is created, everything is transformed," regarding the conservation of mass during changes in the physical state of matter. Thus, it is also possible to transform waste to extract energy. The technologies implemented for the energy conversion of organic biomass and other waste are constantly evolving and aim for ever-greater energy and environmental efficiency at an affordable cost (IEPF 2005). However, to achieve this transformation rationally and consistently, society needs more professional know-how and experts who master not only the main bioenergy technologies but also their environmental impacts, as well as a better understanding of greenhouse gas sequestration and climate change. Objectively, this work must involve multidisciplinary research teams with strong participation from the communities concerned. In Niger, managing waste of all kinds remains a major challenge for government authorities. There is practically no system for managing electromechanical waste. Managing organic waste is equally burdensome for both the population and the government. Therefore, the design of digesters and pyrolyzers for electromechanical waste is an innovative activity to address the general problem of poor waste management. The production and dissemination of such equipment will promote better waste management by encouraging the large-scale production of bioenergy and biofertilizers. Furthermore, this project is innovative because it represents a first in Niger in the creation and implementation of hybrid electricity production systems based on the use of biogas and green charcoal from organic waste and proliferating plant biomass. It is also an innovative method for addressing challenges related to environmental risks.

This project will enable the development of innovative micro-enterprises producing renewable energy and biofertilizers to encourage land restoration on a national scale.

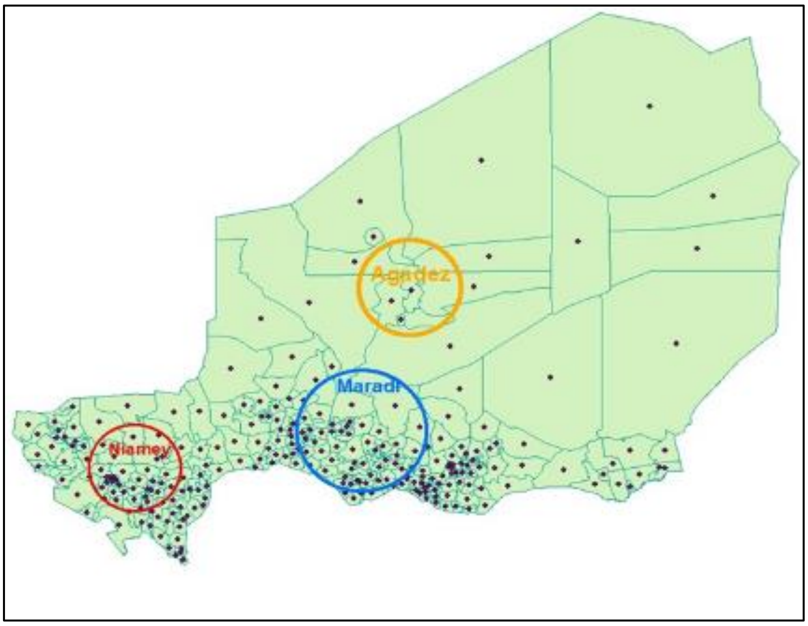

Figure 4 Study Area

Based on population density, urbanization, and agro-ecological characteristics, three key sites were selected for the piloting of this study.

- The city of Niamey and surrounding municipalities have experienced rapid urbanization over the past two decades. It is the largest urban center with a high production rate.The Maradi region is experiencing rapid population growth and urbanization. It is also a region of significant economic activity, with enormous quantities of goods transiting through it from Nigeria.• The Agadez region represents a transition zone between the Sahara and the Sahel. It is the gateway to the sand dunes and presents a significant challenge in the fight against desertificationThese three study areas are characterized by their distinct demographic, agroecological and climatological specialities.. They provide a framework for studies that allows for comparative analyses along a North-Southwest climatic gradient. Several waste disposal sites will be selected to conduct these studies.

2. Conclusion

In Niger, waste management of all kinds remains a major challenge for government authorities. There is virtually no system for managing electromechanical waste. Managing organic waste is equally burdensome for both the population and the government. Therefore, the design of digesters and pyrolyzers for electromechanical waste is an innovative activity to address the general problem of poor waste management. The production and dissemination of such equipment will promote better waste management by encouraging the large-scale production of bioenergy and biofertilizers. It is also an innovative method for resolving challenges related to environmental risks.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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