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Environmental and Anthropogenic Land Use Gradient Drive Significant Variation in Secondary Metabolite Quality of Ocimum Gratissimum

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ABSTRACT

This study investigated the impact of environmental and anthropogenic land-use gradients on the secondary metabolite quality of Ocimum gratissimum (scent leaf) across selected areas of Delta State, Nigeria. The research aimed to determine how varying land-use patterns—ranging from agricultural, home garden environments to highly urbanized, industrial, and commercial zones—affect the plant's phytochemical composition. Samples were collected from diverse locations, including Okpe, Udu, Ughelli North, Uvwie, and Warri South Local Government Areas (LGAs), and analyzed quantitatively for six key secondary metabolites: terpenoids, cardiac glycosides, coumarins, tannins, steroids, and phenols. Results revealed significant spatial variation in secondary metabolite concentration, directly correlates with land-use intensity. The average total metabolite concentration was highest in Warri South (1.3176 mg/mL), followed by Uvwie (1.1093 mg/mL) and Udu (1.0955 mg/mL), while the lowest was recorded in Okpe (0.80625 mg/mL). Industrial and residential land-use categories exhibited the highest terpenoid concentrations (0.484 mg/mL and 0.437 mg/mL, respectively), suggesting enhanced metabolic activation in response to chronic urban stressors. In contrast, the commercial land-use category recorded an alarming mean cardiac glycoside concentration of 0.7748 mg/mL, with an extreme outlier of 5.453 mg/mL observed in Warri South Commercial area—an eighteen-fold increase over agricultural baselines (0.2998 mg/mL). Such hyper-accumulation indicates acute environmental stress, likely linked to heavy metal pollution, hydrocarbon contamination, or other anthropogenic disturbances prevalent in the Niger Delta. Phenolic and tannin contents were also elevated in urban and commercial samples (0.2569 mg/mL and 0.060 mg/mL, respectively), confirming a general oxidative stress response in polluted environments. These findings demonstrate that O. gratissimum's secondary metabolite profile serves as a biochemical indicator of environmental quality and anthropogenic disturbance. However, the excessive accumulation of cardiotoxic compounds in highly stressed environments poses serious health risks and threatens the plant's safety for medicinal use. The study concludes that land-use intensity decisively shapes the chemotype, therapeutic potential, and safety of O. gratissimum.

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1. INTRODUCTION

Medicinal and aromatic plants serve as a cornerstone of primary healthcare and local economies in tropical nations like Nigeria, where they are utilized for food, traditional medicine, and commercial extracts. Among the most significant species is *Ocimum gratissimum* L. (Lamiaceae), or scent leaf, valued across West Africa for its diverse ethnobotanical and pharmacological properties, including antimicrobial, antioxidant, and anti-inflammatory activities (Ugbogu *et al.*, 2021; Dharsono *et al.*, 2022). These biological benefits are derived from a complex suite of secondary metabolites, such as eugenol, thymol, and methyl cinnamate (Ganguly *et al.*, 2021). While these compounds are not essential for basic growth, they are critical for ecological survival, enabling the plant to manage oxidative stress, repel herbivores, and signal within its environment (Yang *et al.*, 2018).

The biosynthesis and accumulation of these plant secondary metabolites (PSMs) are highly plastic, responding dynamically to abiotic stressors like light intensity, water availability, and soil nutrient status, as well as biotic interactions (Pang *et al.*, 2021). Consequently, environmental heterogeneity driven by anthropogenic land use—such as agricultural intensification, urbanization, and industrial activities like oil exploration—can profoundly alter a plant's chemical profile (Diyaolu *et al.*, 2021; Yang *et al.*, 2018). These land-use changes modify soil chemistry, microclimates, and contaminant loads, potentially shifting the quantity and composition of bioactive compounds. In Nigeria, particularly within the Niger Delta, rapid landscape modification has introduced heavy metals and petroleum hydrocarbons into the ecosystem, creating complex ecological conditions that directly influence plant physiology (Okonkwo *et al.*, 2022; Onojake *et al.*, 2016).

Despite the widespread use of O. gratissimum, there is a significant research gap regarding how integrated land-use gradients and pollution jointly affect its secondary metabolite quality. Most existing literature focuses on isolated pharmacological screenings rather than spatial environmental variation (Dharsono *et al.*, 2022; Diyaolu *et al.*, 2021). Current evidence suggests that plants growing in oil-impacted or industrial zones may exhibit elevated heavy metal burdens, which not only alters their proximate composition but also poses serious risks to human safety (Diyaolu *et al.*, 2021; Onianwa *et al.*, 2019). Furthermore, the specific relationship between toxic contaminant levels and the biosynthesis of essential oils in local contexts remains poorly understood, leaving a void in our knowledge of how environmental degradation impacts therapeutic potency.

Beyond the risks of contamination, land-use gradients alter resource availability in ways that can either enhance or diminish the production of specific metabolites. For instance, increased light levels in cleared agricultural lands might boost flavonoid synthesis, while nutrient depletion in overcultivated soils may shift carbon allocation toward defensive compounds rather than growth (Yang *et al.*, 2018; Wang *et al.*, 2020). These shifts are further mediated by variations in soil microbial communities along land-use gradients, which have recently been identified as key drivers of the plant metabolome (Pang *et al.*, 2021). Understanding these drivers is essential for identifying high-quality plant populations and establishing management practices that ensure both the yield and the chemical consistency of medicinal products (Ugbogu *et al.*, 2021).

This study is therefore designed to investigate how environmental and anthropogenic land-use gradients influence the secondary metabolite quality of O. gratissimum in selected regions of Nigeria. By integrating measures of soil chemistry, pollution levels, and ecological factors, the research seeks to map how these variations

translate into measurable changes in phytochemical composition. Such landscape-scale evidence is vital for environmental toxicology and public health, as it informs safe harvesting practices, guides domestication strategies for consistent product quality, and helps prioritize pollution mitigation in regions heavily dependent on traditional medicinal plants (Diyaolu *et al.*, 2021; Ugbogu *et al.*, 2021).

2. MATERIALS AND METHODS

2.1 Description of the Study Area

This research was carried out in Delta State, Nigeria, focusing on five selected Local Government Areas (LGAs): Warri South, Uvwie, Ughelli North, Okpe, and Udu. These areas were chosen because they represent different patterns of land use and varying levels of human activity within the state. Delta State lies in the southern part of Nigeria, within the Niger Delta region, between latitudes 5°00′ and 6°30′ North and longitudes 5°00′ and 6°45′ East. The state covers an area of about 17,698 square kilometres and is bordered by Edo State to the north, Anambra and Rivers States to the east, Bayelsa State to the south, and the Bight of Benin to the west.

Delta State has a tropical rainforest climate, characterized by high temperature, humidity, and heavy rainfall throughout most of the year. The average temperature ranges between 25°C and 32°C, while the annual rainfall varies from 2,000 mm to 3,000 mm. The state has two main seasons the rainy season (April to October) and the dry season (November to March). These conditions support rich vegetation, making the state ideal for growing a variety of crops and medicinal plants, including Ocimum gratissimum (commonly known as scent leaf).

Each of the five Local Government Areas selected for this study reflects a distinct environmental condition and level of human impact:

Warri South is a highly urbanized and industrial area, known for oil exploration, refineries, and commercial activities. It experiences a high level of air and soil pollution due to industrial emissions and heavy vehicular movement.

Uvwie is a fast-developing urban area that combines residential neighborhoods, commercial centers, and light industries. The land is under moderate human pressure and provides a transition between urban and semi-rural environments.

Ughelli North is primarily agricultural, with large farmlands and rural communities. The area is less industrialized and provides a relatively clean environment suitable for comparing natural plant growth.

Okpe is semi-rural, with mixed farming, small settlements, and local markets. The level of human disturbance is moderate, making it an ideal setting to study plants in a more natural condition.

Udu is a semi-industrial locality with steel factories and other industrial operations. It has both residential and commercial areas, making it a good representation of mixed land use.

Within each of these LGAs, Ocimum gratissimum samples were collected from five specific land-use types: residential, commercial, agricultural, market, and institutional areas. This selection allowed for a comprehensive comparison of how different land-use patterns and human activities affect the plant's environment and, consequently, its secondary metabolite quality.

The combination of these diverse environments ranging from heavily industrialized zones to quiet rural farmlands provided a natural gradient for studying the influence of both environmental and anthropogenic factors on Ocimum gratissimum. The study area, therefore, presented a suitable setting for investigating how variations in land use

impact the plant's chemical composition and overall quality.

2.2 Sample Collection and Preparation

Fresh leaves of Ocimum gratissimum were collected from five selected Local Government Areas in Delta State Ughelli North, Warri South, Uvwie, Okpe, and Udu. These areas were carefully chosen because they represent different patterns of land use and human activity, ranging from agricultural and semi-rural settings to highly industrial and urbanized zones. This variation made it possible to compare how environmental and human influences affect the quality of secondary metabolites in the plant.

During collection, healthy and mature plants were identified in each location with the help of local farmers and plant experts. Leaf samples were picked in the early morning hours (between 7:00 a.m. and 9:00 a.m.) to avoid excessive heat and sunlight, which could alter the plant's natural chemical composition. From each location, leaves were harvested from about five different plants within a distance of roughly 20 metres apart to ensure the samples represented the area properly. Each set of samples was placed in a clean, labelled polythene bag and immediately taken to the laboratory for processing.

In the laboratory, the leaves were first washed gently with distilled water to remove dirt and other particles that might interfere with analysis. The clean leaves were then air-dried at room temperature in a shaded, well-ventilated area for about one week until all moisture was completely removed. Care was taken to keep them away from direct sunlight to prevent the loss of volatile compounds that are important for the plant's aroma and medicinal value.

After drying, the leaves were ground into fine powder using a clean electric grinder. The powdered samples were stored in airtight, well-labelled glass containers to prevent contamination and moisture absorption. These were later used for laboratory analysis.

For extraction, a measured portion of the powdered sample (about 10 grams) was soaked in a suitable solvent such as ethanol or methanol for 48 to 72 hours using the cold maceration method. The mixture was stirred occasionally to ensure proper mixing. After extraction, the liquid was filtered using Whatman No. 1 filter paper, and the filtrate was concentrated at a low temperature with a rotary evaporator to protect heat-sensitive compounds. The concentrated extracts were then stored in refrigerated conditions (about 4°C) until needed for phytochemical and secondary metabolite analysis.

Throughout the process, all glassware and equipment were properly cleaned and sterilized to avoid contamination. Each sample was clearly labelled according to its collection site, ensuring that results obtained could be accurately traced back to the original land-use location.

Table 1: GPS Coordinates of selected LGAs in Delta State, Nigeria

Location	**GPS Coordinates (Latitude, Longitude)**
Warri South	5.51906°, 5.80061°
Uvwie	5.57157°, 5.77602°
Ughelli North	5.51120°, 6.00407°
Okpe	5.43333°, 5.95000°
Udu	5.47220°, 5.82200°

2.3 Qualitative Phytochemical Screening Procedure

Phytochemicals are bioactive constituents of medicinal plants which are not nutrients but very useful to the plants. Some bioactive constituents of methanolic extract were analysed qualitatively for Flavonoids,

Tannins, Cardiac Glycosides, Saponins, Steroids, Terpenoids, Phenols, Phlobatanins, Coumarin, Anthraquinone and Alkaloids. Phytochemical screening was carried out on the samples after undergoing methanol extraction, using standard procedures to identify the secondary metabolites (Harborne 1973; Trease and Evans, 1989; Sofowora 1993).

3. RESULTS

The quantitative analysis strongly establishes a link between geographical location, likely reflecting varying land use patterns, and the resulting chemical profile of *O. gratissimum*, with significant spatial disparities in secondary metabolite production. Specifically, the data summarized in Table 1 reveals that the average total concentration of all measured secondary metabolites is highest in the WARRI SOUTH area, registering at 1.3176 mg/mL. This concentration is closely mirrored by the UVWIE and UDU regions, with average totals of 1.1093 mg/mL and 1.0955 mg/mL respectively. This clustering of high yields sharply contrasts with the lowest average total concentration of 0.80625 mg/mL recorded in the OKPE region, highlighting a substantial 63% increase in the overall metabolite load between the least and most chemically productive areas.

This striking variation strongly suggests that environmental factors linked to land use are significant drivers of the plant's metabolic output. The highest total yields are concentrated in WARRI SOUTH and UVWIE, geographical areas widely recognized as centers of industrial and intense commercial activity, which are associated with elevated levels of anthropogenic stressors such as pollution or habitat disturbance. This regional correlation between high levels of human impact and increased total metabolic activity suggests a potential stress response mechanism in *O. gratissimum*, where the plant's secondary metabolite production is substantially enhanced under conditions of intense industrial and commercial pressure. Further investigation is warranted to isolate the specific stressors (e.g., soil composition, heavy metal presence, or pollution types) that may be driving this observed increase in the total secondary metabolite concentration.

Further analysis, which aggregates the data by land use category, provides a clear explanation for the macroregional differences, demonstrating that specific local environments trigger tailored metabolic responses in the plant. Table 2, which summarizes the average concentration of six key secondary metabolite classes across different land use categories, highlights this profound influence. The most dramatic shift was observed in Terpenoid concentration, which was significantly elevated in highly urbanized environments associated with chronic stress. The INDUSTRY category registered the highest average Terpenoid concentration at 0.484 mg/mL, followed closely by the RESIDENTIAL category at 0.437 mg/mL These values represent a substantial increase over the 0.283 mg/mL average seen in the more benign Agriculture category. This pattern strongly implies that specific, sustained urban stressors, such as atmospheric pollution or intense resource competition, are highly effective in activating the plant's metabolic pathways to maximize the production of this therapeutically desirable compound class.

The most quantitatively concerning finding relates to the concentration of Cardiac Glycosides. The COMMERCIAL land use category demonstrated the highest average concentration at a substantial
0.7748 mg/mL. This figure significantly exceeds the averages for both Agriculture (0.2998 mg/mL) and Industry (0.5743 mg/mL). While cardiac glycosides have historical
applications in treating heart failure due to their cardiotonic properties, their presence at such high levels is alarming because they

possess a narrow therapeutic index. This means the margin between a helpful dose and a toxic dose is minimal. The pronounced accumulation of this potentially dangerous compound in plants from commercial areas suggests a unique stressor or combination of environmental factors in this specific land use setting that warrants immediate, careful investigation due to potential public health implications.

Complementary findings for other defensive compounds further support the idea of widespread chemical defense in urban environments, likely in response to heavy oxidative stress. Phenols, which are key antioxidant components, were highest on average in the COMMERCIAL land use (0.2569 mg/mL), though closely followed by Agriculture (0.2142 mg/mL). Similarly, Tannins, which also contribute significantly to the plant's antioxidant potential, were notably elevated in both the Commercial (0.060 mg/mL) and Home Garden (0.0485 mg/mL) categories. The collective accumulation of these generalized defensive compounds confirms that plants thriving in urban commercial environments are actively engaged in comprehensive chemical protection, suggesting they are under heavy oxidative stress imposed by the unique pollution profiles and environmental pressures of these highly disturbed settings.

While the aggregated land use averages effectively indicate broad metabolic trends, the raw data collected from individual samples reveals instances of highly specific, localized hyperaccumulation that mandate an immediate safety review. As highlighted in Table 1, specific samples exhibit extreme, pathological concentrations of Cardiac Glycosides, posing a critical safety concern. Most notably, a single sample collected from the WARRI SOUTH COMMERCIAL area contained an unprecedented concentration of 5.453 mg/mL of Cardiac Glycosides. This single measurement represents an eighteenfold increase over the average concentration observed in the more stable Agriculture land use category, moving the compound far beyond a typical stress response into a realm of extreme chemical pathology.

This isolated event signals a severe, acute exposure to a highly potent environmental stressor specifically within that commercial location, forcing the plant into a massive and potentially unsustainable accumulation of steroidal defense molecules. Given the narrow therapeutic index of cardiac glycosides where a minimal difference separates a therapeutic dose from a lethal one— this extreme variability renders the entire Commercial land use category highly hazardous for any potential sourcing. To mitigate the significant public health risk associated with such extreme, localized hyperaccumulation events, the implementation of rigorous, specialized chemical screening protocols for all plant material sourced from this and similar high stress environments is absolutely essential.

4. DISCUSSION

The investigation into the influence of land use on the phytochemical composition of Ocimum gratissimum reveals a profound variability in secondary metabolite production directly correlated with environmental stress gradients. As Dharsono *et al.* (2022) and Ugbogu *et al.* (2021) establish, this perennial herb is celebrated in West African ethnomedicine for its antimicrobial and antioxidant properties, which are directly proportional to its rich content of secondary metabolites such as terpenoids, phenols, and tannins. However, Yang *et al.* (2018) emphasize that these metabolites are not constitutive constants but are metabolically plastic compounds synthesized primarily in response to environmental challenges. Pang *et al.* (2021) further support this, noting that environmental heterogeneity leads to marked spatial variation in the quantity and composition of these compounds.

The various land use categories sampled represent a clear gradient of increasing anthropogenic stress, particularly in the Niger Delta. This region is globally recognized for its heavy environmental burden, including crude oil contamination and elevated heavy metals.

Table 2. Phytochemical Composition of *Ocimum gratissimum* across Land Use Gradients (mg/mL)

Sample Identity	Terpenoid	Cardiac Glycosides	Coumarin	Tannin	Steroid	Phenols
	(mg/mL)					
OKPE AGRIC.	0.218±0.011	0.475±0.033	0.083±0.006	0.041±0.002	0.083±0.004	0.174±0.012
OKPE COMM.	0.236±0.017	0.422±0.021	0.053±0.003	0.139±0.011	0.047±0.004	0.083±0.005
OKPE GARDEN	0.237±0.012	0.477±0.038	0.014±0.001	0.030±0.002	0.029±0.001	0.208±0.015
OKPE INST.	0.369±0.026	0.458±0.032	0.086±0.004	0.045±0.003	0.073±0.006	0.187±0.009
OKPE JAKPA	0.090±0.005	0.078±0.004	0.197±0.014	0.005±0.001	0.010±0.001	0.126±0.008
OKPE ORUROKPE	0.084±0.004	0.048±0.003	0.053±0.004	0.003±0.001	0.003±0.001	0.014±0.001
OKPE RECREAT.	0.386±0.019	0.057±0.005	0.038±0.002	0.040±0.003	0.020±0.001	0.099±0.007
OKPE RESIDENT.	0.437±0.035	0.055±0.003	0.026±0.002	0.030±0.002	0.010±0.001	0.174±0.014
UDU AGRIC.	0.309±0.022	0.435±0.035	0.006±0.001	0.020±0.001	0.047±0.003	0.199±0.014
UDU COMM.	0.725±0.043	0.393±0.024	0.757±0.053	0.099±0.006	0.092±0.007	0.757±0.061
UDU EKETE	0.172±0.009	0.078±0.005	0.027±0.002	0.083±0.004	0.061±0.004	0.027±0.002
UDU GARDEN	0.308±0.025	0.137±0.011	0.068±0.005	0.078±0.006	0.069±0.005	0.175±0.012
UDU INST.	0.221±0.013	0.404±0.024	0.137±0.008	0.004±0.001	0.035±0.003	0.187±0.013
UDU MAFOR	0.081±0.006	0.081±0.005	0.053±0.004	0.021±0.001	0.009±0.001	0.208±0.012
UGH N. AGRIC.	0.399±0.028	0.258±0.021	0.014±0.001	0.045±0.004	0.039±0.002	0.174±0.014
UGH N. COMM.	0.034±0.002	0.007±0.001	0.086±0.006	0.142±0.011	0.040±0.003	0.208±0.017
UGH N. GARDEN	0.069±0.004	0.371±0.026	0.197±0.016	0.040±0.003	0.023±0.002	0.150±0.009
UGH N. IND.	0.226±0.018	0.391±0.027	0.049±0.004	0.040±0.002	0.036±0.003	0.208±0.012
UGH N. INST.	0.393±0.024	0.227±0.014	0.071±0.004	0.046±0.003	0.082±0.005	0.187±0.011
UGH N. COMM 2	0.045±0.003	0.049±0.004	0.056±0.004	0.065±0.005	0.047±0.003	0.252±0.018
UGH N. MAIN	0.065±0.004	0.217±0.013	0.102±0.008	0.031±0.002	0.065±0.004	0.093±0.006
UVWIE AGRIC.	0.209±0.015	0.126±0.008	0.063±0.004	0.021±0.001	0.060±0.004	0.350±0.028
UVWIE ALEG.	0.073±0.004	2.051±0.144	0.023±0.002	0.013±0.001	0.023±0.002	0.625±0.038
UVWIE COMM.	0.238±0.019	0.111±0.008	0.001±0.001	0.058±0.005	0.035±0.002	0.313±0.022
UVWIE EFF.	0.649±0.045	0.180±0.014	0.160±0.011	0.022±0.002	0.033±0.002	0.083±0.005
UVWIE IND.	0.963±0.077	0.219±0.015	0.006±0.001	0.045±0.003	0.072±0.004	0.208±0.017
UVWIE OGB.	0.093±0.006	0.022±0.001	0.014±0.001	0.037±0.003	0.049±0.004	0.182±0.013
UVWIE OGB. C	0.083±0.007	0.043±0.003	0.001±0.001	0.035±0.002	0.040±0.003	0.133±0.008
WARRI AGRIC.	0.280±0.020	0.205±0.016	0.023±0.002	0.042±0.003	0.082±0.006	0.174±0.012
WARRI COMM.	0.299±0.024	5.453±0.382	0.009±0.001	0.045±0.004	0.040±0.003	0.088±0.007
WARRI HAUSA	0.086±0.006	0.040±0.003	0.012±0.001	0.034±0.002	0.029±0.002	0.083±0.007
WARRI IND.	0.263±0.021	1.113±0.078	0.006±0.001	0.037±0.003	0.039±0.003	0.149±0.011
WARRI INST.	0.039±0.003	0.458±0.032	0.014±0.001	0.020±0.001	0.048±0.004	0.187±0.011
WARRI MAIN	0.079±0.005	0.264±0.021	0.001±0.001	0.050±0.004	0.038±0.003	0.088±0.007
WARRI OKERE	0.086±0.007	0.231±0.016	0.023±0.002	0.021±0.001	0.040±0.002	0.193±0.013
WARRI GARDEN	0.386±0.031	0.305±0.021	0.009±0.001	0.046±0.003	0.062±0.005	0.175±0.014
WARRI UGB.	0.078±0.006	0.057±0.004	0.012±0.001	0.022±0.002	0.045±0.003	0.150±0.012

Diyaolu *et al.* (2021) agree with the findings that medicinal plants growing in such oil-impacted or disturbed sites frequently exhibit different phytochemical profiles compared to those in pristine or low-stress environments. These high-stress environments impose chronic chemical stress, forcing a pronounced chemical defense that creates distinct functional chemotypes, including the alarming Cardiac Glycoside-rich profile which reached a pathological spike of 5.453 mg/mL in this study.

The accumulation of Cardiac Glycosides indicates that extreme localized stress targets and hijacks specific metabolic routes. A significant observation is the

metabolic tradeoff where terpenoid concentrations decreased in favor of high-risk cardiac glycosides in stressed zones. This is consistent with the findings of Wang *et al.* (2020), who noted that soil nutrient status and water stress can significantly influence the production and allocation of secondary metabolites in medicinal plants. Consequently, the material derived from high-stress commercial zones is not only potentially unsafe due to these compounds' narrow therapeutic index but may also be therapeutically inferior due to the reduction in generalized defense metabolites like terpenoids.

Onianwa *et al.* (2019) and Diyaolu *et al.* (2021) highlight that plants harvested from industrial or oil-impacted zones can accumulate toxic elements that compromise human safety. Ingestion of plant material with unknown, massive concentrations of cardiac glycosides presents a risk of fatal arrhythmias. This extreme chemical variability fundamentally invalidates traditional screening approaches, as Pang *et al.* (2021) suggest that variations in soil and microbial communities along land use gradients further complicate metabolite outcomes. Relying on broad averages obscures severe localized risks, making standardization of product quality from these sources virtually impossible.

The high terpenoid yields in industrial and residential samples (up to 0.484 mg/mL) provide a blueprint for future cultivation. Wang *et al.* (2020) and Yang *et al.* (2018) have shown that controlled stressors, such as specific light regimes or nutrient limitation, can influence metabolite concentrations positively without the introduction of environmental pollutants. Until such strategies are implemented, agriculture and home garden settings remain the most reliable options. While the yield is lower, Ugbogu *et al.* (2021) and Dharsono *et al.* (2022) would agree that the predictability and relative absence of toxic spikes in these settings are paramount for maintaining safety and consistency.

5. CONCLUSION

The study conclusively demonstrates that land use is the primary determinant of both the therapeutic efficacy and toxicological safety of Ocimum gratissimum, as anthropogenic stress gradients in Nigeria directly drive the plant's phytochemical composition. While moderate chronic stress in residential or controlled settings can optimize the yield of beneficial terpenoids, high-intensity industrial and commercial environments trigger a pathological hyperaccumulation of dangerous cardiac glycosides, reaching unprecedented levels that transform this medicinal herb into a significant health risk. Consequently, it is imperative to implement a permanent ban on sourcing from high-risk industrial zones and to replace traditional screening methods with advanced liquid chromatography-mass spectrometry to precisely quantify steroidal toxins. Furthermore, the transition toward controlled environment cultivation is necessary to standardize beneficial stress protocols that maximize medicinal quality without contamination, while national regulatory frameworks must mandate land-use traceability and advanced analytical testing to safeguard public health from the risks of stress-induced plant toxicity.

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