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31 Plant Species against Blood Feeding and Disease Vectors Insects: Beyond Anti-Insect Properties, Unvalued Opportunities and Challenges for Health and Sustainability

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Abstract

Plants with bioactive properties are greatly useful in preventing and controlling blood-sucking and disease-vector invertebrates, particularly in developing countries and low-income communities. Their application is a promising alternative to synthetic compounds whose use remains a health, environmental, and economic challenge. However, many are still unknown and unvalued, while others are becoming ignored and threatened. The main objective of this ethnobotanical study is to identify and characterize indigenous and locally grown plants against blood-sucking and disease-vector insects. Salient opportunities and challenges of using these plants are documented and discussed. Semi-structured interviews, using a prepared questionnaire, were conducted with 228 informants. The consensus index (CI) was calculated to analyze the reliability of the collected information. The identified 31 anti-insect plant species belong to 20 botanical families, four morphological categories, and six habitat types. They can be categorized as insecticidal plants (42% of the total), insect repellent (42% of the total), and both insecticidal and insect repellent (16% of the total). More than 54% of these are still abundant in the study area, while about 35.5% have become rare and difficultly accessible. Based on the numerical importance of related anti-insect plant species, the seven targeted blood-sucking insects range in the following decreasing order: Jiggers (16 species) > Fire Ants (9 species) > Flies (8 plants) > Mosquitoes (4 species) > Fleas (2 species) > Bedbugs (1 species) > lice (0 species). The three most commonly used plants, with the highest confirmation indices, are *Tetradenia riparia* (ICs = 0.712), *Eucalyptus globulus subsp. maidenii* (ICs = 0.302), and *Solanum aculeastrum* (ICs = 0.288). The antimicrobial role of many locally grown anti-insect plants and the multiple other associated valorization possibilities are ignored by most informants. Domesticating, propagating, protecting, and promoting the sustainable use of these plants would be an appropriate route for their conservation and continued availability.

Keywords

Blood-Feeding Insects, Anti-Insect Plants, Biopesticides, Sustainability, Burundi

1. Introduction

Blood-feeding and disease vector invertebrates are of health, economic, and scientific concern. The most commonly known include mosquitoes, jiggers, blackflies, tsetse flies, fleas, chewing fleas, ticks, lice, mites, and bedbugs. Generally feeding on humans or domestic animals [1], their bites can cause allergic reactions, blisters, and necrosis [2]. They can carry pathogenic or toxigenic agents (bacteria, fungi, parasites, and viruses) that they may mechanically or biologically transfer to humans [3] [4] and domestic animals [5] (*i.e.*, poultry, bovines, pigs, rabbits, dogs, cats). This leads to severe diseases [4] [5] [6] and economic losses [3] [7] [8]. In recent decades, modern medicine has engaged in prevention and control processes (diagnosis, treatment, vaccination, prevention, diseases surveillance, and vector control). However, vector-borne diseases remain emerging, and their spread remains one of the major concerns facing public health officials and the medical community worldwide [3] [9].

Together, major vector-borne diseases transmitted to humans by mosquitoes (*i.e.*, malaria, dengue fever, lymphatic filariasis, Zika virus disease [10]), sandflies (*i.e.*, Leishmaniasis [11]), lice (*i.e.*, typhus, relapsing fever, and trench fever [12]), triatomine bugs, flies (*i.e.*, cholera, typhoid fever, salmonellosis, dysentery), ticks, tsetse flies, mites, and snails are responsible for about 17% of the estimated global burden of transmissible diseases and more than 700,000 deaths annually [5] [6]. The trend may still increase mainly due to increased population movement, precarious habitats and hygiene conditions, low resources, and low healthcare affordability. Aside from the health impact, blood-sucking insects and their associated pathogens impose a heavy economic burden on individuals and the whole nation. For example, in countries with high malaria endemicity, such as Burundi, the annual loss of economic growth was estimated at 1.3% [7]. Therefore, controlling pathogen vectors can help eliminate these diseases and associated impacts. In this regard, plant-based solutions are among the most adopted way out, particularly in poor communities. It was stated that more than 80% of African rural populations use traditional medicine to deal with health problems [13] [14] [15] [16]. However, fighting against blood-feeding and disease vector invertebrates remains a significant challenge in many countries, including Burundi [17]. Traditionally exploited plants for anti-parasitic and anti-vector purposes are still less documented.

Due to the introduction of modern medicine and synthetic products, local traditional knowledge, transmitted mainly orally, is less and less explored, which could lead to its disappearance [18]. In fact, due to their easy application and relatively quick effects, synthesized insecticides are becoming the most adopted to combat harmful insects. However, although they are physiologically very active, their side effects can sometimes compromise their effectiveness and sustainability. Their intensive use and misuse may cause insects to resist insecticides [19] [20]. Such a phenomenon leads to the continuous development of new products [8] [21], not necessarily less harmful to human health and the environment [22] [23] [24]. Some pesticide's toxic components are not biodegradable and persist in soil, water, and living systems [25]. Therefore, to ensure the sustainability of insect control methods, products of plant origin should be preferred to synthetic substances and as harmless alternatives.

In Burundi and many other countries, many pesticide plant species may remain ignored, or less known and even endangered. For instance, younger generations should be well-informed and sensitized on the importance of anti-insect plants and the necessity of their multiplication and conservation, for which a consistent scientific basis remains crucial. In addition, promoting the use of plant-based solutions to fight against harmful insects requires a holistic approach.

Burundi is one of the most densely populated countries (approximately 463.04 inhabitants per square kilometer in 2020), with an annual population growth rate estimated at more than 2.6% and an increasing high pressure on land and natural resources [26]. In this context, if appropriate strategies are not set up, the pesticide plant species would become more vulnerable and threatened with extinction or would not remain accessible in sufficient quantity and quality for use and application. Plant species with multiple usages and providing, therefore, many opportunities (*i.e.*, medicinal, anti-pest, agro-food, ecologically and economically more viable) have a greater chance to be adopted and preserved.

With this in mind, the main objective of this study is to identify and characterize indigenous or locally grown anti-insect plants to promote their use, multiplication, and conservation. The study focuses on an ethnobotanical investigation of traditionally and currently used plants against blood-feeding invertebrates by local communities. Killing or repellent plants against one or more types of insects, namely mosquitoes, flies, Jiggers (also called sandflies), fleas, bedbugs, lice, and fire ants, are concerned. Conservation strategies or practices and other opportunities that may contribute to overcoming the challenge of loss of interest in these plants are documented.

2. Materials and Methods

2.1. Study Area

The fieldwork was conducted in five communes in the Muramvya province (Muramvya, Mbuye, Rutegama, Kiganda, and Bukeye communes) and one commune in the Kayanza province (Matongo commune) (Figure 1). Mbuye, Kiganda, and Rutegama communes belong to the transition zone between the Mugamba and

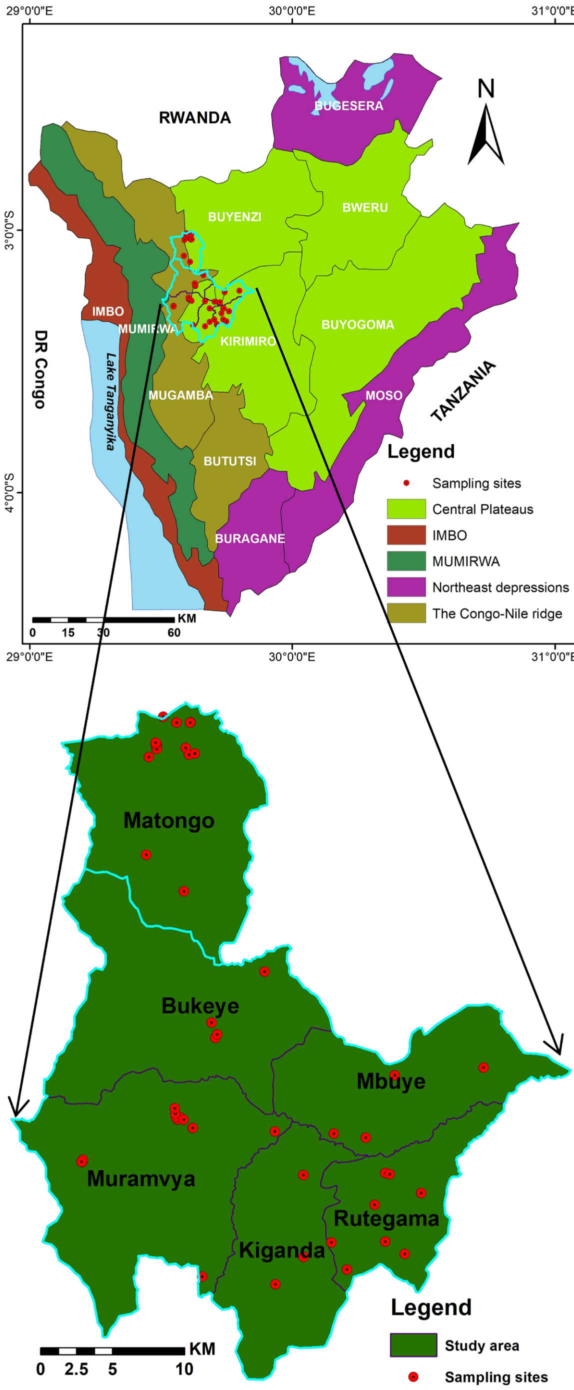

Figure 1. Localization of the study area and sampling sites.

Kirimiro natural regions. Muramvya, Bukeye, and Matongo communes are crossed by the Congo-Nile Divide. The latter consists of a mountain crest with an altitude of 1900 to 2500 meters, separating the drainage basins of the Congo and Nile rivers and supporting the main forest reserves in Burundi (2 forests) [27] and in Rwanda (3 forests). It is characterized by a cool and humid climate, with annual precipitation ranging between 1400 mm and 1600 mm (the most rainfall and wettest area in Burundi) and a temperature averaging 15°C [28]. This makes it a privileged zone for plant diversity and the studied insects. It is also in the surroundings of the ancient royal territory (during the monarchical period).

2.2. Data Collection

Seven types of insects, namely mosquitoes, flies, Jiggers, fleas, bedbugs, lice, and fire ants, are concerned. Potentially anti-insect plants, locally known or used, currently or in the past, against these harmful insects are at the center of the study. The survey used a pre-prepared questionnaire in Kirundi (the local language). In total, 228 respondents, including 123 men and 105 women, were randomly chosen considering the geographical distribution, socioeconomic backgrounds, and age (20 to 80-year-old people) to constitute our survey population. For each anti-insect plant, information was collected on its vernacular name, the used parts and parts to kill or repel insects, and the preparation and administration methods. Some ecological characteristics of the concerned insects and plants were also documented to help understand their presence in the study area. Potential phytochemical and bio-pesticide compounds contained by different plants were also assessed.

The data were collected using a mobile application, "CSEntry/CSPro version 7.5", connected to a "Dropbox" server. Then, they were sent to Excel 2013 software for processing and analysis. For all available recorded plant species, specimens were collected and transported to the herbaria of the University of Burundi and that of the Burundian Environmental Protection Office (OBPE) for botanical identification, floristic evaluation, and conservation.

2.3. Plant Identification

The identification of plants was first made by comparing the specimens collected with those preserved in the herbaria of the University of Burundi and the Burundian Office for Environmental Protection (OBPE). Then, the plant nomenclature was confirmed following the African Plant Database, version 3.3.4, http://www.ville-ge.ch/musinfo/bd/cjb/africa/) and the collection of data on traditional veterinary and human medicine from Africa, available at: http://www.ethnopharmacologia.org/recherche-dans-prelude/.

2.4. Data Processing and Analysis

Data were processed using Excel 2013 software. To confirm the usefulness of the anti-insect plants, the Confirmation Index or Consensus Index, noted ICs, was calculated. The latter represents the ratio between the total number of people having mentioned a plant species (Na) and the total number of people interviewed (Nt) [29] [30] [31]. It is calculated as follows (Equation 1):

$$ICs = \frac{Na}{Nt} \tag{1}$$

Where ICs represent the confirmation Index; Na is the number of people who mentioned the plant species, and Nt is the number of people interviewed.

The Confirmation Index varies between 0 and 1. A low value, close to zero (0), indicates low consensus, meaning that the informants disagree on the use of the pesticide plant. A high value, close to one (1), indicates total consensus on the use of the plant [32].

3. Results and Discussion

3.1. Inventory of Anti-Insect Plants

The list of anti-insect plant species, the parts used in the preparation of remedies, the preparation and administration modes, and consensus indices are provided in Table 1. In total, 31 species divided into 20 botanical families have been identified as anti-insect plants that can be used to control harmful insects. The most represented families are Asteraceae (6 species) and Solanaceae (4 species), followed by the families of Cucurbutaceae, Poaceae, and Lamiaceae, with two species each. The remaining families are represented by a single species each (**Figure 2**).

An ethnobotanical study on spontaneous medicinal plants growing on the northern slope of the Azilal Atlas in Marocco indicated the role of the Asteraceae and Lamiaceae families in fighting harmful insects [33] [34]. A similar role of plants belonging to the Asteraceae family was also noted in Ethiopia [35], a north-eastern African country far from Burundi. Likely, using cucurbitaceous species was reported in the Gura Damole district, Bale zone in the Eastern part of this country [36]. Lamiaceae species also possess repellent, insecticidal, and larvicidal properties [37] [38].

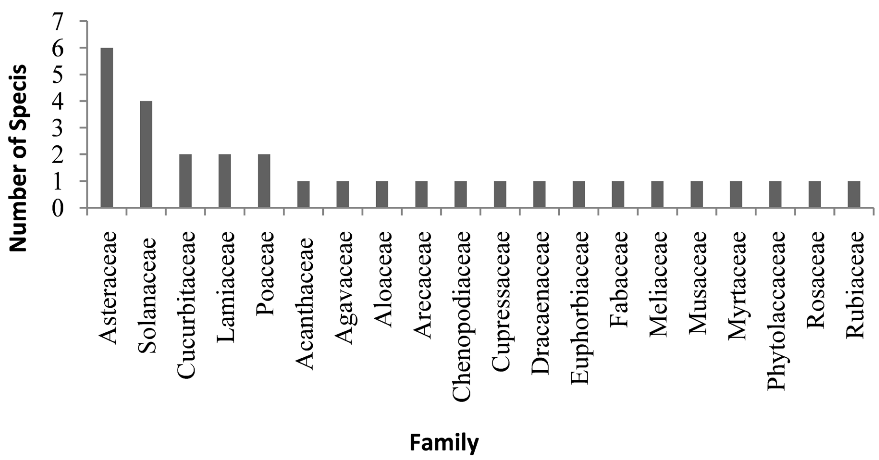

Figure 2. Relative importance of the families of inventoried anti-insects plants.

The 31 recorded anti-insect plant species can be categorized as insecticidal plants (42% of the total), insect repellent (42% of the total), and both insecticidal and insect repellent (16% of the total). The latter group comprises *Nicotiana tabacum, Elaeis guineensis*, *Tetradenia riparia*, *Musa* sp., and *Agave sisalana*.

The number of anti-insect plant species varies from one insect to another. Thus, the seven targeted blood-sucking insects range in the following decreasing order: Jiggers (16 species) > Fire Ants (9 species) > Flies (8 plants) > Mosquitoes (4 species) > Fleas (2 species) > Bedbugs (1 species) > lice (0 species) (**Table 1**). Some plant species are involved in fighting against two or more different insects. These include *Eucalyptus globules* subsp. *Maidenii* (which is repellent for both mosquitoes and flies), *Cupressus* sp. (repellent for both flies and fleas), and *Tetradenia riparia* (repellent for mosquitoes, flies, fire ants, and fleas insecticide). *Musa* sp. (fleas insecticide and fire ant-repellent), *Agave sisalana (*flies repellent and fleas insecticide), *Elaeis guineensis (*killer for fleas and repellent for flies), and *Nicotiana tabacum* (insecticide for bedbugs and repellent for flies).

3.2. Plant Morphology and Habitats

The inventoried plants belong to different morphological types (**Table 2**). Herbaceous plants are the most dominant (55% of the total species), followed by shrub and tree types (19%), while lianas are the least represented (7% of the total species) (**Figure 3**).

The inventoried pesticide plants are found in different habitats (**Table 2**), including degraded forests, savannahs, gardens, crop fields, fallows, roadsides, and house fences. The vast majority of species are found in crop fields (26%), degraded forests (26%), gardens (22%) and fallows (20%) (**Figure 4**).

More than 54% of the identified anti-insect plant species are abundant in the study area (**Table 2**). They mainly include those commonly found and easy to grow in crop fields, gardens, fallows, and artificial forests. They include, among others, *Eucalyptus globulus subsp. Maidenii, Cedrela odorata, Cymbopogon citratus, Tetradenia riparia, Solanum aculeastrum, Musa spp., Euphorbia tirucalli, Tithonia diversifolia, Ageratum conyzoides, Nicotiana tabacum L, Aloe sp., Dracaena afromontana Mildbr., Solanecio mannii, Plectranthus barbatus, and Eleusine coralana.* However, such existence and abundance in human-affected spaces are not guaranteed, particularly due to the pressure on land and plant resources that lead to competition with edible crops. Rare species account for nearly 35% of the total. Among the reasons for the rarefaction of this species are the difficulty of multiplication, specific ecological requirements (for example, forest species), lack of interest in the local population, etc. The rate of species that existed before and which were not available during our work remains low (less than 6.5%). There is no evidence to confirm their disappearance from the region.

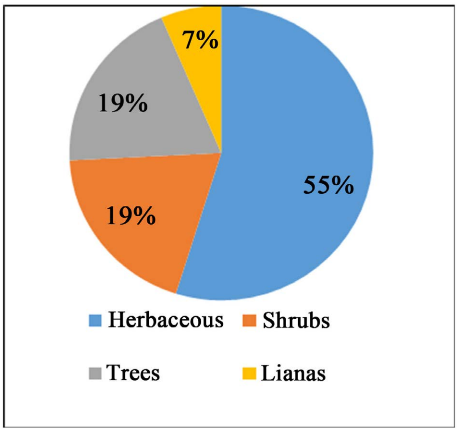

Figure 3. Morphological types of plants.

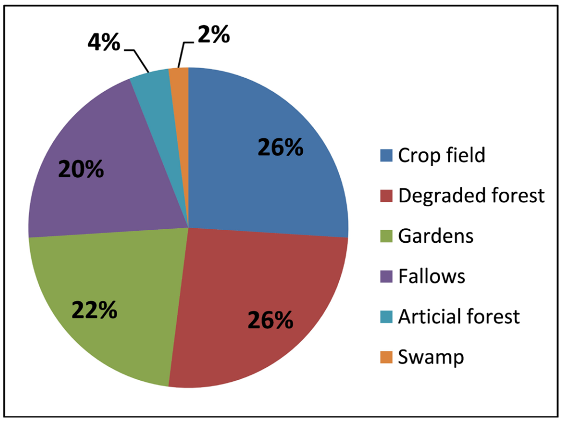

Figure 4. Habitats of the inventoried anti-insects anti-insects plants.

3.3. The Used Plant Parts

The parts of the plants used as anti-insects include (**Table 1**) leaves, barks, roots, seeds, fruits, stems, flowers, rhizomes, and peels. Leaves are the most used plant parts, accounting for 81%, followed by fruits (11%) and rhizomes (4%). Some plants are used whole (4%), justifying the presence of bioactive compounds in all its parts. The predominant use of leaves may be due to that leaves are the site of photosynthesis and the storage of secondary metabolites, including bioactive compounds [39], and leaves are easy to harvest and prepare, particularly for elders, children, and sick people.

3.4. Preparation and Administration Modes

The five most cited modes of preparation of the recipe with their relative importance (in terms of percentage of citation) are as follows (**Table 1**): direct administration, without any particular preparation (26.3%), hand rubbing (23.5%), hanging the leaves in the house (13.2%), maceration and pounding (7.9% each). Other methods, counting for less than 6% each, include burning the plants in the house, juice extraction, grilling, cataplasm, and growing plants with insect repelling or killing volatile excretions near the house (**Figure 5**).

Concerning the administration modes, local application constitutes the most popular mode (42.5% of citations), and the expansion of volatile compounds (40% of citations). The other modes include exposing the place to be protected to the recipe, smoking in the house, and spraying the plant extracts, with 10%, 5%, and 2.5% of the citation, respectively. Crushing the leaves can release a strong odor that is irritating or unpleasant to biting insects [40].

More than 54% of the inventoried anti-insect plants species are still abundant in the study area, while about 35.5% are rare and difficultly accessible. Two plant species, *Phytolacca dodecandra and Elaeis guineensis* that existed in the study area currently not available.

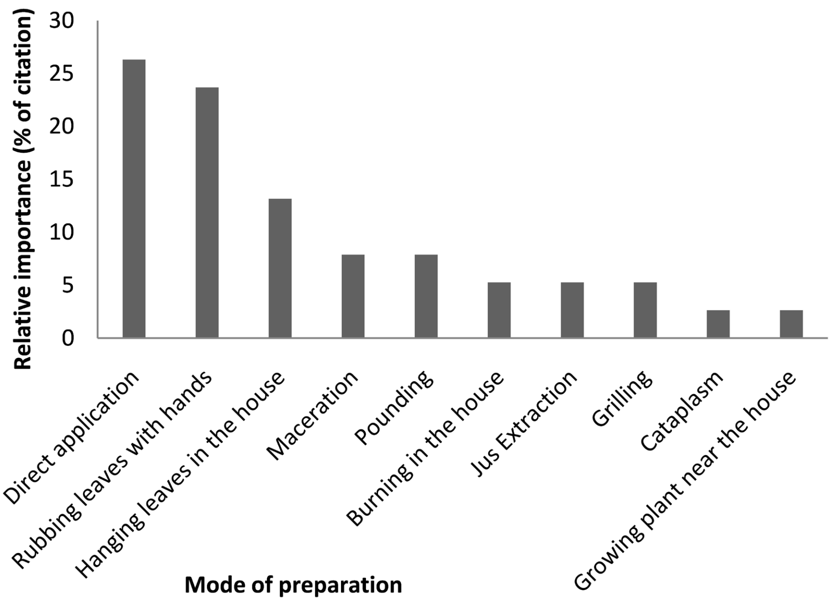

Figure 5. Relative importance of the preparation modes.

Table 1. List of inventoried anti-insect plants, mode of action, used parts, preparation and administration mode, end Consensus index (ICs).

Controled Insectes	Scientific name	Vernacular name	Family	Mode of Action	Used parts	Preparation mode	Administration mode	ICs
Mosquitoes	*Eucalyptus globulus subsp. maidenii*	Umukaratusi wera, mayideni	Myrtaceae	Repellent	Leaves	Hanging Leaves in the House	Expansion of volatile compounds	0.05
	Cedrela odorata	Isederera	Meliaceae	Repellent	Whole plant	Burning inside the house	Extension of smoke	0.01
	Cymbopogon citratus	Icayicayi	Poaceae	Repellent	Feuille	Plant around the house	Expansion of volatile compounds	0.01
	Tetradenia riparia	Umuravumba	Lamiaceae	Repellent	Whole plant	Burning inside the house	Extension of smoke	0.01
Jiggers	*Solanum aculeastrum*	Intobotobo	Solanaceae	Insecticide	Fruit	Grill	Local application	0.288
	Tetradenia riparia	Umuravumba	Lamiaceae	Insecticide	Leaves	Hand rubbing	Local application	0.02

Continued

Jiggers	*Agave sisalana*	Inkaba	Agavaceae	Insecticide	Leaves	Hand rubbing	Local application	0.01
	Rubus pinnatus	Umukerekere	Rosaceae	Insecticide	Leaves	Hand rubbing	Local application	0.02
	Capsicum spp	Ipiripiri	Solanaceae	Insecticide	Fruit	Pounding	Local application	0.02
	Musa spp.	Igitoke	Musaceae	Insecticide	Decomposed Rhizom		Local application	0.02
	Elaeis guineensis	Ikigazi	Arecaceae	Insecticide	Fruit	Extraction	Local application	0.02
	Solanum linnaeanum		Solanaceae	Insecticide	Fruit	Grill	Local application	0.02
	Euphorbia tirucalli	Umunyari	Euphor-biaceae	Insecticide	Latex	Extraction	Local application	0.02
	Tithonia diversifolia (Hemsl.) A.Gray	Ruhanisutwa	Asteraceae	Insecticide	Leaves	Maceration	Local application	0.02
	Ageratum conyzoides	Akarura	Asteraceae	Insecticide	Leaves	Hand rubbing	Local application	0.01
	Virectaria major	Umukizikizi	Rubiaceae	Insecticide	Leaves	Hand rubbing	Local application	0.01
	Chenopodium opulifolium Schrad.	Umugombe	Chenopo-diaceae	Insecticide	Leaves	Hand rubbing	Local application	0.05
	Tephro-sia vogelii	Ntiruhunwa , umubagabaga	Fabaceae	Insecticide	Leaves	Hand rubbing	Local application	0.072
	Momordica foetida	Umwishwa	cucurbita-ceae	Insecticide	Leaves	Hand rubbing	Local application	0.005
	Phytolacca dodecandra	Umuhogohogo	Phytolac-caceae	Insecticide	Leaves	Hand rubbing	Local application	0.01
Bedbugs	*Nicotiana tabacum L*	Itabi	Solanaceae	Insecticide	Leaves	Maceration	Spraying plant ex-tracts	0.02
Flies	*Eucalyptus globulus subsp. maidenii*	Umukaratusi wera, mayideni	Myrtaceae	Repellent	Leaves	Hanging Leaves in-side the house or the area to be protected	Expansion of vola-tile compounds	0.302
	Acanthus polystachyus Delile var. polystachyus	Amatovu	Acantha-ceae	Repellent	Whole plant	Hanging plant in the House	Extension of smoke	0.086
	Agave sisalana	Inkamba	Agavaceae	Repellent	Leaves	Crushing and oil extraction	Spread the oil on the area	0.05
	Cupressus sp	Isederi	Cupres-saceae	Repellent	Whole plant	Hanging Leaves inside the house or the area to be protected	Expansion of volatile compounds	0.05
	Tetradenia riparia	Umuravumba	Lamiaceae	Repellent	Leaves and stems	Hanging Leaves inside the house or the area to be protected	Expansion of volatile compounds	0.01
	Elaeis guineensis	Ikigazi	Arecaceae	Repellent	Fruit	Extraction	Spread the oil on the area to be protected	0.02

Continued

Flies	*Nicotiana tabacum*	Itabi	Solanaceae	Repellent	Leaves	Maceration	spread the oil on the area to be protected	0.01
	Aloe sp.	Ingagari	Aloaceae	Insecticide	Leaves	Cataplasme	Local application	0.01
Fire Ants	*Tetradenia riparia*	Umuravumba	Lamiaceae	Repellent	Leaves	Placing leaves on insects passage or colony	Expansion of volatile compounds	0.712
	Musa spp.	Igitoke	Musaceae	Repellent	Leaves	Placing leaves on insects passage or colony	Expansion of volatile compounds	0.081
	Tagetes minuta L.	Ikimogimogi	Asteraceae	Repellent	Leaves and stems	Placing leaves on insects passage or colony	Expansion of volatile compounds	0.05
	Dracaena afromontana-Mildbr.	Inganigani	Dracaenaceae	Repellent	Leaves	Placing leaves on insects passage or colony	Expansion of volatile compounds	0.02
	Crassocephalum montuosum	Igifurifuri	Arsteraceae	Repellent	Leaves and stems	Placing leaves on insects passage or colony	Expansion of volatile compounds	0.01
	Dichrocephala integrifolia (L.f) O.Ktze	Agatambambuga	Asteraceaea	Repellent	Leaves and stems	Placing leaves on insects passage or colony	Expansion of volatile compounds	0.05
	Solanecio mannii	Umutagari	Asteraceae	Repellent	Leaves	placing leaves on insects passage or colony	Expansion of volatile compounds	0.041
	Lagenaria abyssinica	Umutangatanga	Cucurbitaceae	Repellent	Leaves	Placing leaves on insects passage or colony	Expansion of volatile compounds	0.05
	Plectranthus barbatus	Igicuncu	Lamiaceae	Repellent	Leaves and stems	Placing leaves on insects passage or colony	Expansion of volatile compounds	0.02
Fleas	*Eleusine coralana*	Uburo	Poaceae	Repellent	Finger millet bran	Poundins	Expansion of volatile compounds	0.005
	Cupressus spp	Isederi	Cupressaceae	Repellent	Leaves	Placing leaves on insects passage or colony	Expansion of volatile compounds	0.032
Lice	-	-	-	-	-	-	-	-

ICs = Consensus Index.

Table 2. Anti-insects plant Morphology types, habitats, mode of plantation and availably.

Scientific name	Morphology Type	Habitats	Mode of plantation	Availability
Acanthus polystachyus Delile var. polystachyus	Herbaceous	Fallow land, Degraded forests	Grow naturally	Abundant
Agave sisalana Perrine	Shrub		Planted or Grow naturally	Abundant
Aloe sp.	Herbaceous	Gardens, Crops fields	planted or Grow naturally	Rare
Capsicum spp	Herbaceous	Gardens, Crops fields, Degraded forests	Planted or Grow naturally	Abundant
Cedrela Odorata L.	Tree	Crop fields, Degraded forests	Planted or Grow naturally	Abundant
Chenopodium opulifolium Schrad. ex W.D.J. Koch & Ziz.	Herbaceous	Gardens, Crop fields	Planted or Grow naturally	Rare

Continued

Crassocephalum montuosum (S.Moore) Milne Redh	Herbaceous	Fallows, Swamp	Grow naturally	Abundant
Cupressus sp	Tree	Artificial forests, Hourse Fences	Planted	Abundant
Dichrocephala integrifolia (L.f.) O. Ktze	Herbaceous	Gardens	Grow naturally	Rare
Dracaena afromontana Mildbr.	Shrub	Gardens, Crop fields	Planted or Grow naturally	Abundant
Elaeis guineensis Jacq.	Tree	Gardens, Crop fields	Planted	Not available
Eucalyptus globulus subsp. maidenii (F. Muell.) Kirkp.	Tree	Artificial forests, fallows	Planted	Abundant
Lagenaria abyssinica (Hook.f) C. Jeffrey	Lianas	Forests, Gardens	Planted or Grow naturally	Rare
Momordica foetida Schumach	Liana	Fallow land, Degraded forests, Crop fields, fallows	Plantedor Grow naturally	Rare
Musa spp.	Herbaceous	Gardens, Crop fields	Planted	Abundant
Nicotiana tabacum L.	Herbaceous	Gardens, Crop fields	Planted	Rare
Phytolacca dodecandra L'Her.	Herbaceous	Degraded forests	Planted or Grow naturally	Not available
Plectranthus barbatus Andrews	Herbaceous	Degraded forests, Crop fields, fallows	Planted or Grow naturally	Abundant
Rubus pinnatus Willd.	Liana	Degraded forests	Grow naturally	Abundant
Solanecio mannii (Hook.f) C. Jeffrey	Tree	Gardens, Degraded forests	Planted or Grow naturally	Rare
Solanum aculeastrum Dunal	Shrub	Fallows, Degraded forests	Grow naturally	Abundant
Tagetes minuta L.	Herbaceous	Fallows, Crop fields	Grow naturally	Abundant
Tephrosia vogelii Hook.f.	Shrub	Fallows, Crop fields	Planted or Grow naturally	Rare
Tetradenia urticifolia (Baker) Phillipson	Shrub	Gardens, Crop fields	Planted or Grow naturally	Abundant
Tithonia diversifolia (Hemsl.) A.Gray	Herbaceous	Fallows, roadsides,	Grow naturally	Abundant
Virectaria major (K. Schum.) Verdc.	Herbaceous	Degraded forests	Grow naturally	Rare
Ageratum conyzoides L.	Herbaceous	Crop fields	Grow naturally	Abundant
Cymbopogon citratus (DC.) Stapf	Herbaceous	Gardens	Planted	Rare
Eleusine coralana	Herbaceous	Crop fields	Planted	Less Abundant
Euphorbia tirucalli L.	Tree	Crop fields, Hourse fences	Planted or Grow naturally	Abundant
Solanum linnaeanum	Herbaceous	Fallows, Swamp	Grow naturally	Rare

3.5. Efficiency, Opportunities, and Challenges for the Sustainability

3.5.1. Anti-Lice Plants

From this study, none of the recorded anti-insect plant species identified is useable against lice species. However, the population of our study area recognizes the existence of this type of bloodsucking insect and its associated diseases.

Epidemic typhus is known as a severe acute disease with high mortality if not treated. Wartime would be the most catastrophic moment regarding lice-borne pathogens and diseases, as was the case for Burundi during the civil war of 1993 - 2002. In 1997, Burundi faced the largest epidemic of typhus associated with trench fever after its resurgence in 1995 and 12 years of absence in the country [41]. This disease, whose pathogen agent (bacteria of the *Rickettsia* genus) was transmitted to humans by *Pediculus humanus corporis* [42], affected more than a hundred people in the country, particularly in 5 provinces, including Kayanza and Muranvya that are concerned in this study [43]. Russia alone recorded more than 25 million cases and more than three million deaths during the Revolution. Different regions, including North Africa, southern Italy, and Eastern and Central Europe, were also affected during and after World War I and II [44]. Sporadic cases were later observed across the world (in North Africa, North America, Russia, China, etc.) and, recently, lice-borne *Rickettsia prowazekii* exhibited a minimum prevalence of 7.3%, a maximum prevalence of 21.2% and an overall prevalence of 5.57% in refugee camps and detention centers in the east of 176 Africa, Burundi and Rwanda [44] [45].

Our respondents recognized the relationship between the lack of hygienic conditions and the spread of lice-borne pathogens and diseases. They confirmed that improving hygiene conditions, *i.e.*, shaving hair and heating clothes with hot water or removing clothing invaded by lice, effectively helps control lice and prevent lice-associated diseases. Such hygienic measures would not only be effective against typhus but also against other lice-borne diseases such as relapsing fever, trench fever, and plague [12] [41] [44].

3.5.2. Anti-Bedbugs Plants

Nicotiana tabacum was the only reported plant species with anti-bedbug properties. However, its use for insecticidal purposes remains limited to isolated cases particularly due to ignorance or adoption of pesticides. This justifies the related low consensus between respondents (ICs = 0.02). Despite the diversity of this arthropod group, no distinction in specific sensitivity was reported by respondents.

Bedbugs remain of great public health and socioeconomic concern. The genus of *Cimex* comprises different species (*i.e.*, *C. lectularius*, *C. hemipterus*, *C. columbarius*, *C. pipistrelli*, *C. dissimilis*, and *Oeciacus hirundinis*) that most feed on humans and animals, including domestic animals, birds, and bats. Their bites are generally associated with cutaneous and allergic reactions (ex. their allergens can trigger asthmatic reactions [41]), anemia, stress, anxiety, sleep disturbance, secondary infections, and mental health impacts. *Cimex lectularius* and *Cimex hemipterus* have recently become a common societal pest [41] and have given rise to high clinical interest [1] [12]. From the majority of our respondents (more than 65%) and the literature [41], bedbugs are typically prevalent in the most densely populated or frequented places (school dormitories, homes, hotels, detention centers, health care environments, etc.).

Bedbugs population is rapidly increasing (100 - 500% increase annually) [46]) and spreading worldwide [41] [47], while fighting against them is becoming financially and ecologically more challenging [12]. People generally resort to conventional methods to clean up infested places, objects, or multiplication sites (clothing, mattresses, sheets, etc.). However, using pesticides in schools may lead to acute illness among school employees and students, with an incidence rate of 35% to 65% [12] [48]. It was also estimated that the cost of disinfecting a house using standard insecticides and replacing infested belongings was estimated at nearly $2500 - $3000 (USD) per infestation [47], whereas dealing with cleaning invasions of commercial and industrial workplaces may cost millions of dollars [49]. Very few Burundians, particularly those in the study area, would be able to afford these costs.

Thus, to cope with bedbugs, it is mandatory to set up a fully integrative approach [12], taking into account cost-effectiveness, health, and ecological efficiency. In this regard, the application of *Nicotiana tabacum,* as a natural alternative to synthetized chemicals meets all of these expectations. Despite being non-edible, *N. tabacum* economic importance makes it one of the most extensively cultivated plants worldwide mainly for the cigarette industry and for human consumption needs. Due to its adaptability to both tropical and temperate conditions, Burundi offers a well-indicated cultivation terrain.

Besides its nicotine, the principal chemical components, *N. tabacum* contains in its leaves, stems, roots, and floors more than 4000 chemicals or secondary metabolites compounds, including phenolic compounds, nicotphenols A - C [50], cembranoids, flavonoids alkaloids, and terpenoids [51]. The bioactivity of *N. tabacum* compounds leads it to be efficiently used against various parasites, bacteria (*i.e.*, *Escherchia coli* [52], *Klebsiella pneumonia*, *Listeria monocytogenes*, *Viridans streptococci*, *Mycobacterium phlei* [53], *Mycobacterium tuberculosis* [54], *Staphylococcus aureus* [52] [55]), virus [51] [55] [56], HIV (Human Immunodeficiency Virus) [50] [56], *Cryptococcus neoformans* [57], *Streptococcus pyogenes* [57]*, Bacillus subtilis* [52], fungi such as *Candida albicans* [53] [55] [57], *etc.* Research continues to prove the bioactivity of *N. tabacum* components against many bedbugs associated pests or pathogens [12], including *Bartonella quintana*, *Burkholderia multivorans*, *Trypanosoma cruzi*, *Rickettsia parkeri*, hepatitis B virus, hepatitis C virus, methicillin-resistant *Staphylococcus aureus*, vancomycin-resistant *Enterococcus*, *Penicillium chrysogenum*, *Stenotrophomonas maltophilia*, *Enterobacter hormaechei*, *Bacillus licheniformis*, and *Staphylococcus saprophyticus* [46] [47] [58], etc. The latter may be responsible for more than 40 human communicable diseases, although no evidence has proved their transmission by bedbugs [12] [58] [59], even for the viruses that they may harbor, such as hepatitis B virus [60] and HIV [1].

It should also be noted that the use of *N. tabacum* is extended to managing many other human and veterinary ailments such as ulcers, respiratory tract infections, cancer, cough, snake bite [61], rheumatic swelling, skin diseases, painful piles, and stings [62]. It is also used against termites [51] [55] [56] and as a vermifuge [61] [63] [64] [65].

Based on these examples, it is clear that *N. tabacum* presents various tangible opportunities. Therefore, it deserves to be valued, developed, and preserved. However, many challenges need to be considered and addressed. *N. tabacum* cultivation development is influenced by several factors, including soil conditions (fertility and physicochemical properties), environmental conditions, cultural practices, economic and health considerations, and farming environmental impact.

Compared to other crops, tobacco is extremely demanding in terms of growing space and essential soil nutrients (nitrogen, phosphorus, potassium, magnesium, calcium, etc.), fertilizers, agrochemicals, and growth regulators [66] [67]. This is likely to lead to the quick loss of soil fertility [68], soil erosion, and land degradation, deforestation (to find new appropriate soil) than many other crops.

In Burundi, tobacco cultivation is declining in favor of other crops, less nutrient demanding, more economically profitable, sources of food for humans and domestic animals, and less or not dangerous to health and the environment. According to our survey, the scarcity of arable land and the increasing lack of fertilizers are the main factors. Furthermore, awareness of the health impact of smoking and relative prevention measures, especially by avoiding smoking, has reduced the number of people interested in this crop. Among the people interviewed, no one thinks of making this plant a crop of choice for family economic development. Furthermore, apart from its use in cigarettes and as an anti-bedbug, more than 80% of our respondents were unaware of the other benefits of *N. tabacum*, including its antimicrobial role.

3.5.3. Anti-Mosquitoes Plants

Four plant species, namely *Eucalyptus globules* subsp. *maidenii*, *Cedrela odorata*, *Cymbopogon citratus,* and *Tetradenia riparia*, are cited as mosquito repellent.

a. *Eucalyptus globulus* sub sp. *Maidenii*

Eucalyptus globulus subsp. *Maidenii* is recognized as the most appropriate mosquito repellent and the most abundant in the study area. Of the Mosquitoes genera, *Anopheles*, *Aedes*, and *Culex* are the most involved in transferring pathogens responsible for various diseases, including malaria, dengue fever, lymphatic filariasis, chikungunya, Zika virus disease, West Nile fever, yellow fever, and Japanese encephalitis [10]. In Burundi, malaria, caused by *Plasmodium* species, remains the most prevalent disease and the leading cause of mortality and morbidity [69] [70] [71], followed by diarrheal diseases, acute respiratory infections (ARI), malnutrition, and AIDS [7]. Malaria, plasmodium, and mosquitoes are all endemic across the whole country. In 2009, malaria was responsible for more than 48% of deaths in children under five years of age and more than 50% of reasons for consultation in hospitals and health centers in the country. The malaria epidemic raged in 2019, reaching 843,000 cases per million inhabitants [69] and more than 2.600 deaths, whereas 8,571,897 malaria cases and 3170 deaths were recorded in early 2020 [72] against 5,957 deaths in 2021 [73].

Essential oil from *Eucalyptus globulus* subsp. *maidenii* exhibits strong mosquito-killing and repellent activity [74] which may be due to the phenolic acids released by its leaves. *Eucalyptus globulus* essential oil contains in high concentration 1,8-cineole, a substance that is also contained in the leaves of *Salvia* and *Artemisia*, and is endowed with several healing properties [75]. However, it was reported that *Eucalyptus citriodora* would be most effective [76] against mosquitoes and flies.

Apart from the anti-mosquitoes activity, *Eucalyptus globulus* extracts, particularly its essential oil have a broad spectrum of biological activity that can attract much scientific, medicinal, pharmacological, and industrial interest. As shown hereafter, they include anti-bacterial, anti-fungal, insecticidal/insect repellent, anti-nematodes, herbicidal, anti-mites, and acaricidal [76].

- **Antibacterial activity** (*i.e.*, bioactivity against *Listeria monocytogenes, Bacilus subtilis, Staphylococcus aureus, Enterococcus spp, Shigella flexneri, Klebsiella pneumoniae, Salmonella choleraesuis, Salmonella enteritidis, Proteus mirabilis, Xanthomonas vesicatoria, Enterobacter aerogenes*. Such an antibacterial property makes 1, 8-cineole capable of healing wounds and increasing the permeability of the skin. It is also effective in treating blisters, burns, cuts, and sores [77]. However, it may not be active on some other microorganisms, including *Escherichia Coli* or *Pseudomonas aeruginosa* [78].

- **Antifungal activity:** Essential oil from *Eucalyptus globulus* is capable of inhibiting the activity of various fungi species such as *Aspergillus flavus* [79], *Aspergillus parasiticus* [79] [80], *Alternaria solani*, *Fusarium oxysporum* f.sp. *niverum*, *Usarium graminearum, Rhizoctonia solani,* and *Venturia pirina,* all of them exhibiting the inhibiting activity of globulol [81], *Fusarium solani*, *Sclerotinia sclerotiorum*, *Rhizoctonia solani* [82], *Fusarium moniliforme* [80], *Trichophyton mentagrophytes*, *Microsporum gypsum* (filamentous forms) [83], and *Candida albicans* [83] [84] [85] (the three last ones exhibiting more activity of *Eucalyptus citriodora* oil than *E. globulus)*, *Saccharomyces cerevisiae* [84] [85], *Candida parapsilosis* [85], etc. Owing to this antifungal activity, together with anti-bacterial, anti-insect, and anti-oxidant properties, extracts and essential oil from *Eucalyptus globulus* constitute potential natural food preservatives, a valuable component for food stock management. To support the safety of such use, *eucalyptus* oil is on the list of Generally Regarded as Safe established by the Food and Drug Authority of USA and classified as non-toxic; it was approved as a flavoring agent in foods, candies, and confectionery items. At low concentrations, it is extensively used in soaps, detergents, and perfumes [76].

- **Anti-inflammatory and analgesic effects:** Due to its 1,8-cineole content, essential oil from *E. globulus* exerts an anti-inflammatory and analgesic activity [86] associated with anti-oxidant properties [75] [87]. It may inhibit the formation of prostaglandins and cytokines by monocytes, hence the anti-inflammatory effect, and thus, can be used as a painkiller, particularly in muscular pain and rheumatic diseases [75].

- **Anti-cancer and hypoglycemic effect**: Ongoing researches have not yet proven tangible results.

- **Anti-cancer and hypoglycemic effect**: Ongoing research has not yet proven tangible results.

- **Antiviral, expectorant, and mucolytic activity** (direct stimulation of the secretory cells of the bronchial mucosa, helps thin bronchial secretions to expel easily, relaxing the smooth muscles of the airways) [88]. *Eucalyptus* essential oil exerts spasmolytic effects in the attenuation of inflammatory responses caused by viruses, in particular respiratory diseases [89].

It is used to treat headaches, sinusitis, asthma, sore throats, nerve pain, skin infections, urinary tract infections, ear infections, bronchitis [90], and Herpes Simplex Virus (HSV1 and HSV2) [91] [92]. Using eucalyptus essential oils is one of the alternative antiviral solutions to the absence of an adequate therapeutic remedy for treating human infectious diseases of viral origin, such as influenza, SARS-COV-2, and recently COVID-19. These essential oils serve as complements for the treatment of symptoms or to exert effects on possible pharmacological targets of viruses [89].

In Burundi, eucalyptus has long been used in the form of drinkable solutions or inhaled vapors to relieve respiratory problems, chest pain, headaches and the flu. The recent COVID-19 pandemic has caused a widespread rush to use eucalyptus extract to combat this pandemic. However, since it is combined with other solutions, including pharmaceutical products, it becomes difficult to estimate its effectiveness level. Other uses include being a source of notable essential oils, distillates, tannins, nectar, pollen, shade, honey flora, etc.

The first Eucalyptus plantations began in Burundi in 1931 [93] [94]. Since then, it has been widely adopted and cultivated. The planted areas increased continuously, reaching 18.000 ha in 1973, 25.000 ha in 1976 [93], and more in the following years. Its expansion across the country results from many reasons. The first reasons are the higher wood and charcoal quality and its multiple uses. It is the most preferred wood energy source in Burundi, where wood is the principal source of domestic energy and accounts for 96.6% of total energy use, 77% of all charcoal being used in cities [95]. It is also extensively used as a construction material, wood industry (raw material and energy sources), and many other composite products. The second reason is the Government's efforts. Besides the national reforestation programs, landowners (*i.e.*, religious missions, public and private companies, households, and individuals) are constantly encouraged to plant more trees on their properties. Seeds and plants have long been distributed to the population freely.

The third reason is its high tolerance and adaptability to severe ecological conditions (desiccation, low soil fertility, degraded land, fire) that facilitate its adaptation and growth in different types of soil, climate, and topography of Burundi. The unpalatability of its leaves makes it non-palatable for insects and herbivorous animals [76]. Its high regeneration capacity, fast growth, short rotation, high yield per unit area and year coppicing ability, and easy silvicultural management make it an important cash crop [96] for many Burundians.

Despite its versatile importance, *Eucalyptus* presents some significant ecological challenges, despite the existing controversial views. *Eucalyptus* species are alleged to contribute to increasing the drying up of water sources and marshes, and that leads the Government to impose its uprooting and the cessation of its cultivation near rivers, water sources, and marshes. Its suspected contribution to soil desiccation, soil acidification, and allelopathic effects that are considered responsible for the reduction of biodiversity and productivity in planted environments arouses the distrust of agri-breeders. However, Burundians agree on the difficulty of finding a natural alternative to this Australian native plant species. By combining better silvicultural and energy yield, good quality wood, adaptability, and a socio-economic contribution, eucalyptus's versatile importance seems to mask criticism of its disadvantages. Accordingly, and from a broad scientific conviction [93] [94] [95], it is possible to predict its long-term existence and availability in Burundi and many other countries with similar ecological and socio-economic conditions. Our respondents acknowledge that these plant species is incorporated into the lifestyle of many people. They are committed to preserving it to allow it to be permanently available in sufficient quantities.

b. *Cymbopogon citratus.*

Cymbopogon citratus, also known as Citronella or lemongrass, is known as a mosquito-repellent plant species. Its use is becoming more popular in Burundi, particularly in urban and semi-urban areas where it is much more cultivated in home yards. Its leaves are currently sold in many markets in the capital of Bujumbura. *C. citrates* is a perennial, fast-growing, and aromatic grass. Originating in tropical countries of Asia (Indochina, Indonesia, and Malaysia), Africa, and the Americas, it is widely cultivated worldwide, particularly in tropical regions [97]. Its most reported chemical components include terpenes, alcohols, ketones, aldehyde and esters, flavonoids, and phenolic compounds [98]. Its essential oil contains various bioactive constituents, including aromatic compounds (myrcene and limonene), antimicrobial compounds (*i.e.*, citral), insecticidal compounds (*i.e.*, geraniol), citronellol, geranyl acetate, neral, and nerol [99], Terpinolene, Terpinol Methylheptenone [98].

Citronnela insecticidal activity is not limited to controlling mosquitoes. Studies reported the same activity against houseflies, Musca domestica, *Phemacoccus solenopsis* (a damaging insect for cotton crops, vegetables, and fruits), house dust mites, *Dermatophagoides farinae* and *Dermatophagoides pteronyssinus,* with more efficiency than *Azadirachta indica* (neem) leaf extract [100].

Citronella extracts mainly the essential oil, can be used to counteract harmful microorganisms, including bacteria (*i.e. Pseudomonas fluorescens*, *Salmonella enteritidis, Micrococcus luteus*, *Serratia marcescens* [101], *Staphylococcus aureus*, *Salmonella typhi*, *Bacillus aureus*, *Escherichia coli* [102], *Enterobacter cloacae* and *E. aerogenes* [103], *Shigella flexneri, Y*east [99] and fungi [98] [99] [104], *i.e.*, *Candida krusei, Candida albicans, Penicillium aurantiogriseum*, *Penicillium expansum*, *Penicillium chrysogenum, and Penicillium italicum* [101], *Aspergillus* species (*i.e.*, Aspergillus *ocraceus*, *A.orizae*, *A. fumigatus* and *A. parasiticus*) [105], *Aspergillus niger*, *A. terreus*, *A. flavus and Penicilium citrinum* [106], *Scropulariopsis brevicaulis*, *Fusarium poae*, *F. verticillioides*, *Trichophyton mentagrophytes*, *T. rubrum*, *Epidermophyton floccosum* and *Microsporum gypseum* [107], *Microsporum canis* [108], *Malassezia furfur* [109], *Candida oleophila*, *Hansenula anomala*, *Saccharomyces cerevisiae*, *S. uvarum*, *Schizosaccharomyces pombe,* and *Metschnikowia fructicola* [110], *Alternaria alternata*, *Fusarium oxysporum* and *Penicillium roquefortii* [111], etc. Their impressive anti-amoebic, anti-diarrheal, anti-filarial, and anti-inflammatory [97] [98] [104] activities have attracted more scientific and public attention. *C. citratus* is involved in improving gut/colon function and boosting the immune system.

Due to its anti-microbial activities, including the anti-food spoiling microorganisms activity, lemongrass essential oil can efficiently serve as a natural preservative of food [112], *i.e.*, bakery products, vegetables [110], and yogurt [99], etc., that represents a great opportunity in food technology. Thus, it constitutes a promising alternative to synthetic microbicides and other sanitation techniques in food storage and packaging. However, their effectiveness is microbial and dose-dependent [99].

Lemongrass is also used to treat coughs, elephantiasis, influenza, headache, arthritis, leprosy, and malaria [113]. In-depth studies are conducted to confirm and divulge their various other effects such as anti-diabetic [104], anti-cancer [114], anti-obesity, anti-nociceptive, free radical scavengers, and anti-oxidant activities [97] [110], anti-mutagenicity, hypoglycemic, neurobehavioral effect [98] [115], anti-VIH (anti oral trash due to candida albicans), anti-hypertension, anti-tumor, anti-amebic, anti-ascaris, hypocholesterolemic, hypolipidemic, and larvicidal activities.

As reviewed by Shah and colleagues [98], the chemical composition of an essential oil varies depending mostly on the nature and age of the plant and the geographical origin. Therefore, as the bioactivity of essential oil depends on its phytochemical constituents, studies should be conducted to confirm the reported differences in the ethnopharmacology of *C. citratus* between countries. For example, it was shown that *C. citratus* was applied to treat sore throat, empacho and as an emetic in Argentina, as antispasmodic, analgesic anti-inflammatory, antipyretic, diuretic, and as a sedative in Brazil, as a hypotensive for catarrh and rheumatism in Cuba, as renal antispasmodic and diuretic in Egypt. In India, *C. citrates* is used for the treatment of gastric troubles, cholera, severe headache and fever and as a sedative for the central nervous system. It also serves as an emmenagogue in Indonesia and Malaysia, as a condiment, as stomachic and anti-diabetes in Thailand, and for healing bone fractures and wounds in Minnesota (USA).

Due to its volatility and its typical lemony aroma, *Cymbopogon citrates* oil is used as a deodorant in cosmetics, toiletries, insecticides (bio-pesticides), and spend grass in the agricultural. It plays an essential role in the pharmaceutical and chemical industry where it is incorporated in the manufacture of various products, including cosmetics, perfumes, fragrances, detergents, soaps, and aftershaves, and the food industry where it serves as a culinary flavoring [97].

More importantly, *C. citratus* application is of great opportunity in plant protection (as a repellent, bio-fungicide, bio-insecticide, and bio-herbicide, etc.) [103] and in the livestock sector (feed additives, feed conservation, veterinary medicine purposes). Feed supplementation with lemon grass leaves allows for improving daily animal growing rate [116] [117] and health [117]. In fact, regarding nutritional value, *C. citratus* contains various nutritional elements, including vitamins A and C, folic acid, iron, copper, magnesium, potassium, manganese, calcium, and zinc [118] which are essential for both human and animal nutrition. In vitro experiments have shown that lemongrass oil may efficiently help modulate rumen fermentation. The latter consists of reducing methanogenesis and ammonia nitrogen production irrespective of dietary substance [119] that contribute to reducing greenhouse gas production.

In Burundi, tea made from Citronella leaves, alone or in combination with extracts of *Zingiber officinalis* rhizome serves to treat flu, colds, and headaches. Very recently, citronella leaves were combined with eucalyptus and Ginger and taken orally (as liquor extracts) or by inhaling vapors as a potential remedy for Coronavirus 2019. Citronella is also used as an ornamental plant and for agricultural purposes (*i.e.*, as spent grass in coffee plantations). From our survey, the essentiality of *Cymbopogon citratus*, including its uses as an antibiotic, food additive, food preservation, bioherbicide, etc., is very ignored in the study area.

From the survey and literature, *C. citrates* is not only associated with broad health-beneficial effects, but it is appropriate to point out some of its negative impacts. Prolonged use of extracts from this plant may lead to some side effects, including nephrotoxicity effects, particularly due to ethanolic extract [120], and derma-toxicity effects associated with its skin irritant compounds [121]. The plant is also associated with allelopathic effects. Plant species such as *Bidens pilosa* and *B. subalternans* [122] [123], *Lactuca sativa* [124], *Echinochloa crus-galli* [123] [125], *Paniccum virgatum*, *Chlorus barbata*, *Euphorbia hirta*, *Stachytarpheta indica* [126] are some of the reported affected. Inhibition of seed germination and seedling growth, cytotoxicity, and genotoxicity are among these allelopathic effects. The latter can serve as a basis for using Citronella extracts as bioherbicides. Conversely, they can lead to an affliction on local biodiversity by reducing sensitive species abundance.

c. Tetradenia riparia

Tetradenia riparia is well-known in our study area as a mosquito-repellent plant. It is a deciduous shrub with intensely aromatic leafage and reaching 2 to 5 meters in height. It is widespread and well-adapted in Burundi, where it is grown in various places, mainly as fences for houses, home gardens, crop fields, fallows, roadsides, and paths. *Tetradenia riparia* possesses several chemical compounds. Its crude extracts and essential oil from the leaves stems, and flower buds contain mainly tannins, terpenoids, steroids, phenols, phenolic acids, flavonoids, saponins, anthocyanins, and alkaloids [127]. Numerous remarkable bioactive phytoconstituents have been well-documented [128]. These are potentially active against various pests, including blood-sucking insects, human and animal pathogens, and foodborne disease microorganisms.

Regarding the anti-insect properties, our respondents revealed that *T. riparia is repellent for* mosquitoes, flies, and fire ants while being an insecticide for jiggers. *Tetradenia riparia* is bioactive against *Anopheles gambiae, Aedes aegypti, Leishmania* species, T*rypanosoma* species, and *Rhipicephalus sanguineus* [129]

[130]. The most reported sensitive bacteria [127] [131] include *Bacillus cereus*, *Serratia liquefactions*, *Serratia marcescens*, *Salmonella typhi*, *Escherichia coli*, *Proteus vulgaris*, *Staphylococcus epidermidis*, *Bacillus subtilis*, *Enterococcus faecalis*, *Klebsiella pneumoniae*, *Lactobacillus casei*, *Mycobacterium tuberculosis*, *Pseudomonas aeruginosa*, *Salmonella enterica*, *Staphylococcus aureus*, *Staphylococcus epidermidis*, *Streptococcus mitis*, *Streptococcus mutans*, *Streptococcus salivarius*, *Streptococcus sanguinis*, *Streptococcus sobrinus*, *Listeria monocytogenes,* and *Micrococcus kristinae*, etc. Its antifungal activities are known for *Candida albicans*, *Aspergillus versicolor*, *Penicillium ochrochloron, Listeria monocytogenes* [131], *Mycobacterium smegmatis*, *Microsporum canis*, *Trichophyton mentagrophytes*, etc. In addition, *T. riparia* is traditionally applied for its anti-viral activity, such as the potential anti-VIH/AIDs activity [128]. Due to its anti-microbial activity, *T. riparia* may be used against food-spoiling organisms, *i.e.*, as a protective agent in cereals, legumes, or beans in warehouses.

Owing to the immense diversity and efficacy of its bioactive phytochemical constituents, *T. riparia* is found in different countries, mainly in Africa (*i.e.*, in Burundi, Ouganda, Kenya, Rwanda, Tanzania, and South Africa) and Brazil. In these countries, it is recognized as an efficient natural alternative to the synthetic chemical used for the fight against blood-sucking insects and pathogen vectors and for the treatment of a wide range of diseases. The latter include those originating from bacterial, fungal, and viral infections, parasites (*i.e.*, tick, *Leishmania*, and helminths), such as respiratory problems, diabetes [128], cough, diarrhea, fever, malaria, dengue [132], mycoses, boils, abscesses. In the field of traditional medicine, it is used in healing hemorrhoids, ulcers, skin diseases like itching, scabies, psychotic, dyspepsia, excitement, blocked fallopian tubes, emetic, bilharzia, body rushes, and cleaning wounds [128], as well as analgesic, anti-tumor, antioxidant, anti-cariogenic, anti-spasmodic, anti-pyretic, anti-allergic and anti-inflammatory, vermifuge, tennifuge, anti-amoeba, and Diuretic.

All these uses are not to be generalized for all countries or regions. In Burundi, *Tetradenia riparia* is mostly used to treat candidiasis, toothache, fever, diarrhea, inflammatory diseases [133], flu, bronchitis, sore throat, cough, migraine, and headache.

During the recent COVID-19 pandemic, some Burundians tried to use it alone or in combination with *Eucalyptus globulus*, and *Tetradenia urticifolia,* as a natural remedy against this pandemic virus. The emerging use of natural product extracts from various medicinal plants as mitigation measures against the COVID-19 pandemic was adopted in different developing countries. However, a scientific basis is still required to evaluate its safety and efficacy [128].

In other countries, *T. riparia* serves for the treatment of ear infections, eye infections, stomach, weakness in pregnancy [134] and febrile convulsions [135] in Uganda, pneumonia in the Democratic Republic of Congo, respiratory infections, chest pain, influenza, chronic cough, shortness of breath and a runny or blocked nose, headache, chills, cough, tiredness, sleep disorders or sleepless nights in South Africa [136], parasitic worms, stomach-ache, fungal infections, chest rheumatism in Democratic Republic of Congo (DRC) [137], wounds, sores and scabies in Tanzania [138] and DRC [137], etc. Variation of their local uses depends on various factors, including the originality of people, culture, and beliefs [128], the collection time, soil, plant growing location, climate, seasonal variation, altitude [132] [139], etc.

In addition, considering the range of its medicinal virtues, *T. riparia* is less exploited in Burundi and other countries. From this study, three main reasons may justify the low adoption of this medicinal plant as a remedy for various medical conditions. Firstly, the level of knowledge of *T. riparia* bioactivity remains low, generally based on ancestral knowledge and oral transmission in general. Secondly, there is little interest among younger generations due to the widespread adoption of synthetic products that are easy to use. The third reason is the insufficient scientific basis for determining effectiveness, dosage, contra-indication, and the side-effects of each treatment.

Unlike certain plants with various allelopathic effects, *T. riparia* is well-appreciated in agroecology and agroforestry. It can serve as fodder, melliferous, anti-erosion plant, fertilizer, and shady, ornamental (due to its flowers) and for Crop protection against pests.

Owing to its various bio-active properties, together with its easy multiplication and adaptation to different habitats, its strong capacity for regeneration after cutting, and its agroforestry and agro-ecological interest, this plant should be recommended for domestication and multiplication projects with a view to continuous exploitation and in sufficient quantity.

d. *Cedrela Odorata*

Cedrela odorata, also named Spanish cedar, is identified as a mosquito-repellent plant in this study. It is a medium to large tree reaching more than 30m in height. It is naturally found in humid ecosystems, specifically in tropical forests and mesophilic mountain forests, with a large distribution in American tropical forests [140], and a concerning spreading trend in West African natural forests [141].

From physicochemical analyses [142] [143] [144], *C. odorata* essential oil and extracts contain different chemical compounds, mainly sesquiterpene hydrocarbons (the most dominant [143] [144]) and oxygenated sesquiterpenes. However, their phytochemical composition, quality, and quantity vary depending on the plant (sample) origin, the climate, and the extraction methods [142] [144]. Due to the bioactivity of some of its phytochemical components, *C. odorata* essential oil and extracts are of medical and ecological interest.

From our survey, *C. odorata* is acknowledged as a mosquito-repellent plant species despite the low consensus between respondents (ICs = 0.01). Recent studies have proven the effectiveness of using *C. odorata* extracts as a biological insecticide against termites (*Reticulitermes* sp.) [140] that are capable of devouring almost any type of wood and destroying habitat, wooden structures such as frames, floors and beams, furniture, fence posts, clothes, books, paper, racks, etc.

Volatile oil from the stem bark of *C. odorata* is an efficient protectant against *Sitophilus zeamais* (Coleoptera) [145] [146], a cosmopolitan pest that seriously damages stored cereal grains (up to 30% yield loss) [146]. *C. odorata* extracts exhibited an anti-feedant activity and toxicity on the *Ostrinia nubilalis Hubner*, and *Callosobruchus maculatus* [145], *Anthonomus eugenii* (a pepper weevil causing an annual economic loss estimated at 70 to 80 million dollars in Mexico) [147].

Regarding the antimicrobial activity, sensitivity tests revealed *C. odorata's* potential antibacterial and anti-fungal activities. Sensitive bacteria include *Bacillus cereus* [143] [148], *Staphylococcus aureus*, *Escherichia coli*, *Enterococcoccus faecalis* [148], *Pseudomonas aeruginosa, Bacilus* subtilis [149], *etc., and v*arious and anti-fungal activity including for dermatophytes, *candida species, Scytalidium dimidiatum*, *Malassezia* species, and *Pneumocystis carinii* [150], *Aspergillus niger, Penicillium notatum*, *Mucor mucedo* and *Candida albicans* [149].

C. odorata is also involved in various other medical conditions. Extracts from its leaves and stems are used to relieve vomiting and indigestion and for hemorrhage control. The leaf infusion is a tooth and ear pain reliever, while the stem is an antipyretic and abortifacient [140]. It may also be involved in healing malaria, intestinal infection, intoxication, poor digestion, and kidney diseases [151]. *In vitro* and *in vivo* tests on rats showed the potentiality of using *C. odorata* as an anti-hyperglycemic, anti-diabetic, and anti-oxidant [152].

Concerning the socio-economic role, *C. odorata* has great economic value. This is due to its attractive wood quality which makes it a commercially important tree species in many producing countries, including Latin America and the Caribbean. Due to its lightweight (specific gravity of 0.47), high strength, easy workability, low and even shrinkage [153], rot- and termite-resistance, and insect-repellent smell, timber from *C. odorata* is suitable for many uses. *C. odorata* wood is used for light construction, furniture, ship construction, musical instruments (ex., guitar), plywood, interior design, veneer, cigar boxes, wardrobes, etc. *C. odorata* can also serve as a source of firewood and charcoal.

Ecologically, this plant, native to tropical America, has been introduced in other tropical regions worldwide, including Africa, Asia, and the Pacific Islands, mainly as a timber tree and a promising forest restoration species [154]. Thus, it is integrated into national reforestation programs or cultivated on private properties. Due to its numerous seeds and their easy dispersal, it can grow naturally.

C. odorata is on the IUCN (International Union for Conservation of Nature) Red List of Threatened Species in different parts of the Americas. However, it paradoxically exhibits invasive behavior in various countries [154], with a remarkable impediment to natural forests, plantation, and the biodiversity of the environments where it develops [141] [154] [155].

In Burundi, all agroforestry and silvicultural tree species are quasi-exotic. *C. odorata* is grown alongside other most disseminated tree species, including *Grevillea robusta*, *Maesopsis eminii*, *and Alnus acuminate.* All of them are often planted in association with shrubs such as *Calliandra calothyrsus*, *Leucena leco-cephala*, etc., to contribute to wood production, non-wood forest products, agroforestry systems with the aim of water and soil conservation, increasing soil fertility and adapting to climate change.

3.5.4. Anti-Flies and Anti-Fleas Plants

Regarding the flies repellent plant species, the consensus indices of the informants vary from 0.01 to 0.302 (**Table 1**), the higher consensus indices being for *Eucalyptus globules* subsp. maidenii (CIs = 0.302) and *Acanthus polystachyus* var. *polystachyus* (CIs = 0.086). For this category of insect, only *Aloe* sp. has been cited as an insecticide. These plant species may indistinctively act against different fly species, including *Musca domestica*, *Glossina* spp, *Stomoxys calcitrans*, *Haematobia irritans*, and *Tabanus* sp., which are among the main vectors of pathogens [156]. *Musca domestica* alone is a vector of more than 100 different pathogens [156] [157], including various foodborne pathogens. The latter comprise parasites such as *Entamoeba, Ascaris, Enterobius, Strongyloides, Ancylostoma, Necator, Trichuris, Metastrongylus, Haematopinus*, *Cryptosporidium, Giardia, Taenia, Hymenolepis* [158] and *Habronema* [159]*.* Conversely, Glossina spp. can transmit to humans and animals different Trypanosma species, including *T. vivax, T. congolense, T. simiae, T. brucei, T. gambiense, and T. rhodesiens.*

For plant species used as flea repellent, two insect repellent species, *Cupressus* sp. And *Eleusine coralana*, were cited, with respective consensus indices of 0.032 and 0.005 (**Table 1**). *Cupressus sempervirens* leaf extracts are very effective in controlling houseflies, while the smoke produced by burning the whole *Cupressus lusitanica* plant is used in Ethiopia to repel mosquitoes and houseflies [37].

3.5.5. Anti-Jigger Plants

All the 15 identified anti-jigger plants are insecticides (**Table 1**). The highest consensus indices are associated with *Solanum aculeastrum* (CIs = 0.288) and *Tephrosia vogelii* (CIs = 0.072), whereas *Momordica foetida* exhibited the lowest consensus index (0.005). The following examples illustrate the multipurpose use of anti-jigger plants.

a. *Solanum aculeastrum*

Phytochemical analysis revealed that *Solanum aculeastrum* contains steroidal alkaloids, including β-solamarine, solamargine, solasonine, solasodine, solaculine, tomatine, and tomatidine [160]. Their associated bioactivity renders *S. aculeastrum* extracts efficient in fighting against not only insects but also parasites and pathogens, including bacteria species (*i.e.*, *Bacillus cereus, Staphylococcus epidermidis, Staphylococcus aureus, Streptococcus pyogenes, Micrococcus kristinae)* and fungal species (*i.e.*, *Aspergillus flavus*, *Penicillium notatum*) [161], *protozoan species such as Leishmania,* transmitted by sandflies of the genus *Phlebotomus or Lutzomyia* [11]*. S. aculeastrum* extracts are also reported as molluscides [160] [162] and antioxidants. *S. aculeastrum* berries have long been used as an alternative treatment to cancer [163]. However, its anticancer activity is still scientifically controversial [163] [164]. Fighting against jigger fleas helps prevent typhus and trench caused by infection by Rickettsia species transmitted to humans by insects.

Handling and using *S. aculeastrum* fruit extracts requires caution because they can cause health and ecotoxicological effects. Toxicity tests on male Wistar rats have revealed potential immunodeficiency and hypersensitivity to the aqueous extract of the fresh, unripe berries of *S. aculeastrum* [165]. It was reported acute toxicity symptoms, including hypoactivity, respiratory distress, and epistaxis. *S. aculeastrum* fruit extracts adversely affected the normal functioning of the blood, liver, and kidney. *S. aculeastrum* is one of the most common fish-poisoning plants. Its use, as a simple method of fishing, should be strictly avoided [166]. Its non-selective toxicity on aquatic organisms (*i.e.*, insects, larvae, fishes, etc.) adversely affects the food chain and ecosystem functioning.

b. *Tephrosia vogelii*

Phytochemical analysis revealed the presence of various components such as retinoids, steroids, glucosides, tannins, rotenones isoflavones, chacones, flavanones, flavanols, prenylated flavonoids, alkaloids, saponins, balsam, cardiac glycosides, phenol and volatile oil on which relies its bioactive properties, *i.e.* Retinoid based entomotoxic properties, anti-bacterial, anthelminthic, and fish poison properties [167]. According to the World Agroforestry Centre [168], rotenone was classified by the World Health Organization as a moderately hazardous or Class II pesticide. Thus, *T. vogelii* was widely applied to pest control before the invention of DDT (Dichlorodiphenyltrichloroethane) and is still usable in controlling pests in the field and storage or on domestic animals. Using *Tephrosia vogelii* crude leaf extracts to control jiggers and worms in livestock production systems has been rated equal to synthetic insecticide [169]. Compared to many synthetic pesticides, the most known advantage is its rapid breakdown (within 3 - 5 days after application [168]. Laboratory tests on mice exhibited acute toxicity of its crude methanolic leaf extract with similar effects to rotenone poisoning in mammals. Neurological disorders and hepatic, renal, and cardiac necrotic changes are among the most predominant effects [170]. Acute toxicity of extracts from *T. vogelii* was also observed in relevant species in aquaculture ponds, such as Rotifers, Cyclops, mosquito larvae [167], water fleas (*i.e.*, *Daphnia magna*, Crustacea), adult fishes, and fish larvae [167] [171]. From these few examples, *Tephrosia vogelii* and *Solanum* species should be carefully handled, for example, by preventing skin contact.

c. *Tithonia diversifolia*

In the study zone, *Tithonia diversifolia* is known and used as a jigger killer. Our informants are not well-informed on its other potentially beneficial properties, including the bioactivity against mosquito species (*i.e.*, *Anopheles gambiae, Aedes aegypti,* and *Culex quinquefasciatus),* the antimalarial activity [172], the bioactivity against root-knot nematodes (*i.e.*, *Meloidogyne incognita*, *M. arenaria*, *M. hapla*, *M. javanica*, *M. enterolobii*) [173] and against ants (*i.e.*, workers of

Atta cephalotes L.) [174]. *T. divesifolia* is also used for its anti-inflammatory and analgesic activities compost [173]. Extracts from aerial parts of *T. diversifolia* contain terpenoids and flavonoids components [175] [176] [177] on which depends its traditional use for the treatment of malaria, diabetes, menstrual pain, diarrhea, hepatomas, hepatitis, hematomas, and wound healing [175] [178]. Owing to its free radical scavenger capacity and also by induction of protective cellular systems involved in cellular stress defenses and in adipogenesis of mesenchymal cells, *T. diversifolia*, exhibited health-promoting properties [175]. However, the use of *T. diversifolia* extracts for disease treatment may raise concerns over its safety [179]. Laboratory tests have shown that prolonged exposure to higher doses of *T. diversifolia* extracts adversely affects the kidneys and liver [179] [180].

Ecologically, *Tithonia diversifolia,* considered an ornamental plant, has exhibited invasive behavior, particularly due to its rapid growth rates, the easy and massive seed dispersion by wind, animals, and water, high adaptation ability in various habitats (disturbed sites, fallows, and ruderal areas, along roadsides, watercourses, wastewater evacuation gutters, and waste disposal sites) and different field soil and moisture conditions. *T. diversifolia* is used as green manure for Nitrogen sources and is recommended as a key component of compos [173].

Water extract from leaves, stems and roots of *Tithonia diversifolia exhibited* allelopathic effects on shoot growth, root growth, and *seedling growth* of various plants such as rice [181] [182], maize [183], cabbage, cucumber, lettuce, mung bean, tomato, oat, sorghum, wheat, crabgrass, slender amaranth, jointvetch, rice flatsedge, onion, radish, and itchgrass [182].

3.5.6. Anti-fire ant plants

Plants used as fire ant repellents have a consensus index between 0.01 and 0.712. The most cited plants within this category include *Tetradenia riparia* (ICs = 0.712), *Musa* sp. (CIs = 0.081), *Tagetes minuta* (CIs = 0.05), *Solanecio mannii* (CIs = 0.041). Other plant species have consensus indices of less than 0.05. Fumigation of the whole *Tagetes minuta* plant, in a mixture with *Eucalyptus globulus* leaves, keeps insects away from attacking living spaces [37]. Concerning *Solanecio mannii*, its leaves contain volatile compounds that have repellent properties that help control subterranean termites, *Macrotermes natalensis* [184]

4. Conclusions

This study aimed to contribute to the knowledge of the local population on plants that can be used against blood-sucking and disease vector insects and to the knowledge of their different health, ecological, and economic potentials with a view to promoting their multiplication, conservation, and sustainable valorization.

We identified 31 anti-insect plant species, including those against fleas (16 species), fire ants (9 species), flies (8 species), mosquitoes (4 species), fleas (2 species), and bedbugs (1 species). No anti-lice plant was reported. They belong to 20 botanical families with a dominance of the Asteraceae family (19.4%). These plants are of different morphological types, mainly herbaceous (55%), shrub and tree (19%), and liana (7%) types. They are mainly found in crop fields (26%), degraded forests (26%), gardens (22%), and fallows (20%), where they mostly grow naturally. As modes of preparation and administration, these biopesticide plants are largely administered without prior preparation and by the expansion of volatile compounds. The use of different plant parts, including leaves (81%), fruits (11%), rhizomes (4%), and the whole plant (4%), may mean the presence of bioactive compounds in various plant parts, but in different concentrations. Based on the consensus indices, we could conclude that the population of the study area is well-informed on plants against flies, fleas, and fire ants. Conversely, there may be a lack of confidence in using plant-based solutions against mosquitoes, fleas, and bedbugs. Up to now, the inventoried anti-insect plants have vast unvalued health, economic, and ecological potential as demonstrated through the examples of plant species, including *Nicotiana tabacum*, *Eucalyptus globulus*, *Cymbopogon citratus*, *Tetradenia riparia*, *Cedrela Odorata*, *Solanum aculeastrum*, *Tephrosia vogelii*, and *Tithonia diversifolia*. Ignorance and lack of interest could be the main reasons.

On the other hand, the valorization of these plants is subject to numerous challenges. For example, in the context of galloping demography, high population density, scarcity and overexploitation of arable land, and the competition with edible crops, their abundance in anthropized and non-protected areas does not guarantee their continued existence. In this context, plants combining several advantages, including medicinal, pharmacological, biopesticide, better energy yield, commercial roles, etc., are more likely to interest the population called to adopt, multiply, protect, and conserve them. Regarding their biopesticides and medicinal application, the lack of reference for appropriate doses, health, and ecological risks related to abusive use and safety use, the growing use of synthetic chemicals, and the deficit of an effective related communication system are increasingly deepening the lack of interest, particularly among the younger generations. Anti-insect plant species such as *Eucalyptus globules* subsp. maidenii, *Nicotiana tabacum*, *Musa* sp., *Cupressus* sp., and *Cedrela Odorata* are planted for their socio-economic benefit. However, up to now, domestication of biopesticide plants remains insignificant and very limited to individual private initiatives and for very few species. It should be extended to government programs or private partners with appropriate resources. Conversely, some species that existed in the past are rarely available, while two species (*Phytolacca dodecandra* and *Elaeis guineensis)* could have disappeared in the study area. Therefore, conservation strategies are required, including domestication and specific protection mechanisms for plants and potentially appropriate growing areas.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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