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Developments in research on the nutritional health-promoting properties of three traditional leafy vegetables commonly consumed in sub-Saharan Africa

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ABSTRACT

Introduction: Amaranthus cruentus (*Amaranthaceae*), *Ocimum gratissimum* (*Lamiaceae*), and *Solanum macrocarpon* (*Solanaceae*) are leafy vegetables widely used for nutritional and medicinal purposes throughout sub-Saharan Africa. Their medicinal properties are related to the presence of bioactive compounds and other widely documented components. Progress in research activities on bioactive compounds and health-promoting properties of these three leafy vegetable species were analyzed using bibliometric analysis coupled with content analysis.
Methods: Data from 296 articles selected from Scopus and Web of Science databases were screened to identify publication trends, plant parts used, profiles of bioactive compounds, and analysis methods used to determine some potential health-promoting properties.
Results: A growing interest in this research field was observed, particularly over the five-year period 2010–2014 (>35.0% of publications), with more attention on *O. gratissimum* and *S. macrocarpon* than *A. cruentus*. Leaves were the main plant parts used although growing conditions were most often not reported. Considerable efforts were made to identify bioactive compounds in the three leafy vegetables while the mechanisms governing the health-promoting properties of *A. cruentus* and *S. macrocarpon* leaf extracts are not yet fully known.
Conclusion: Multidisciplinary studies integrating agriculture, environment, nutrition, and health within the same analytical framework must be undertaken for a better understanding of factors affecting the nutritional and health-promoting properties of these leafy vegetables.

1. Introduction

The state of malnutrition in sub-Saharan Africa is characteristic of the double burden of malnutrition with a high prevalence of undernutrition and increasing over-nutrition along with overweight, obesity, and diet-related non-communicable diseases (Melaku et al., 2019; Popkin et al., 2020). The double burden of malnutrition is a major public health concern that continues to increase in sub-Saharan African countries (Melaku et al., 2019; Popkin et al., 2020), wherein it can take many forms depending on where (country, community, household, or individual) and how it occurs (Davis et al., 2020; Popkin et al., 2020). Meanwhile, there is an urgent need to find the right strategy to solve this problem, which adds more burden to the already struggling health systems of sub-Saharan African countries (Melaku et al., 2019). In this perspective, changes in diet and health behaviors are likely to have major effects on the individual's current and future health. Current solutions to address the malnutrition burden are primarily aimed at improving diet quality through increased intake of nutrient-dense and

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health-promoting foods (Melaku et al., 2019; Davis et al., 2020; Popkin et al., 2020). Thus, in low-income settings, consumption of these types of foods that are available, accessible and affordable could be a valuable option to promote good health and strong nutritional status.

Several varieties of traditional vegetables found in sub-Saharan Africa are essential components of African diets (Adedokun et al., 2016; Chagomoka et al., 2017; Meldrum et al., 2018). Although evidence of health benefits associated with leafy vegetable consumption exists, the low consumption prevalent in sub-Saharan Africa deprives Africans of enjoying a nutritionally balanced diet (Babalola and Akinwande, 2014; Chagomoka et al., 2017; Mibei et al., 2017). Traditional leafy vegetables supply humans with significant amounts of macronutrients (proteins and fibres), micronutrients (Na, K, Ca, Mg, P, Fe, and Zn), vitamins (ascorbic acid and β-carotene) and non-nutrient phytochemical compounds that can contribute to a healthier food menu (Achikanu et al., 2013; Louis et al., 2017; Mibei et al., 2017). However, in spite of the nutritional potential of traditional leafy vegetables, only a few species have been domesticated in sub-Saharan Africa, while large numbers grow wild in forests or cultivated fields (Akanbi et al., 2010; Musa et al., 2017). Currently, the availability of leafy vegetables is mostly rainfall dependent (Akanbi et al., 2010; Musa et al., 2017), which can mean scarcity and increased cost during the off-season. Therefore, there is a need to re-orientate the African population towards off-season vegetable production in order to ensure all-year-round availability.

In Benin Republic, 187 plant species are potentially valued as traditional leafy vegetables. They are gathered mostly from the wild or cultivated in various agroforestry systems and are consumed by rural residents as part of their daily food menu (Dansi et al., 2008; Achigan-Dako et al., 2010). Only 18 species out of these vegetables have great economic importance in the country. In this respect, *Amaranthus cruentus* (*Amaranthaceae*), *Ocimum gratissimum* (*Lamiaceae*), and *Solanum macrocarpon* (*Solanaceae*) were identified as leafy vegetables of great importance in food and medicinal systems (Dansi et al., 2008; Achigan-Dako et al., 2010). Biochemical data revealed that these leafy vegetables are rich in nutrients endowed with health-promotion abilities, which could prevent the harmful effects of under-nutrition and its micronutrient deficiencies (Ademoyegun et al., 2013; Ayodele et al., 2015). Pharmacological investigations have shown that these leafy vegetables possess antioxidant, anti-inflammatory, anti-nociceptive, anti-tumor, hepato-protective, hypoglycemic, hypolipidemic, and hypotensive activities (Salawu et al., 2013; Irondi et al., 2016). Among these health-promoting properties, antioxidant, anti-diabetes, anti--obesity, and antihypertensive activities are altogether associated with a reduction of the risks of metabolic syndrome and oxidative stress-related diseases resulting from excessive nutrient intake (Irondi et al., 2016). However, previously published reviews on *A. cruentus, O. gratissimum* and *S. macrocarpon* did not explore in detail the nutritional and health benefits of these vegetables, nor did they take into account most of the different analytical methods used in the research articles (Prabhu et al., 2009; Yang and Ojiewo, 2013; Achigan-Dako et al., 2014). Thus, much remains to be done in terms of literature review of the nutritional and health benefits of *A. cruentus, O. gratissimum* and *S. macrocarpon*, which depend on environmental factors and cultivation practices (Babalola and Akinwande, 2014; Musa et al., 2017; Meldrum et al., 2018).

Given that leafy vegetables are of great importance to food and nutritional security (Chagomoka et al., 2017; Meldrum et al., 2018), there is an urgent need to better understand various aspects related to structural and health-promoting properties of the phytochemical components. To achieve this goal, bibliometric analysis is a valuable tool to assess the scientific activities and determine research trends within the field (Luo et al., 2018; Yeung et al., 2018). The key concept of bibliometric analysis is the output measurement of academic and scientific research publications through data derived from online databases using statistical analysis tools (Luo et al., 2018; Yeung et al., 2018). The results obtained from bibliometric analysis can contribute to the identification and analysis of the main driving agents of the research field and can stimulate innovative and timely research thoughts for researchers, analysts and managers in the different decision-making processes. However, a review of the literature related to nutritional and health benefits of *A. cruentus, O. gratissimum* and *S. macrocarpon* using bibliometric analysis does not exist. Therefore, the objective of this study was to analyze the research trends on the bioactive compounds and health-promoting properties of *A. cruentus, O. gratissimum* and *S. macrocarpon* on a global level using bibliometric analysis coupled with content analysis.

2. Methodology

2.1. Literature search strategy

A review of the literature related to bioactive compounds and functional properties of *A. cruentus, O. gratissimum* and *S. macrocarpon* was conducted using bibliometric analysis combined with content analysis (a technical tool for examining a sample of documents in a systematic way) to take advantage of the two approaches. A web-based search of articles published in the scientific journals indexed by Scopus and Web of Science databases was performed. No time limit was used for the literature search in order to achieve a comprehensive understanding although the Web of Science and Scopus collections started in 1969 and 1972, respectively. The literature search was conducted using the following steps: (i) keyword identification; (ii) filters of refinement; (iii) exclusion and inclusion criteria; (iv) content analysis; and (v) data extraction.

2.2. Selection criteria

The literature review was conducted according to the flowchart presented in Fig. 1. The binomial scientific names of the plants (*Amaranthus cruentus*, *Ocimum gratissimum* and *Solanum macrocarpon*) were used as keywords in each database. The search scope was limited to "journal articles" while excluding books, conference papers, dissertations, letters, notes, reviews, and theses. Fields of interest including biological sciences, chemistry and biochemistry, food sciences and technology, food and beverages, medicine, nutrition, pharmacology, and plant sciences were used to refine the search due to their relevance as information sources. Consequently, an exhaustive list of 2305 articles published up to 2018 (inclusive) was obtained from the two databases. This timespan was defined in order to consider all publications made within a full year period. Inclusion of an article in the review is linked to its clear statement of the experimental and analytical studies design conducted on bioactive compounds and potential health benefits of *A. cruentus*, *O. gratissimum* or *S. macrocarpon*. In this review, "bioactive compounds" refer to minerals, carotenoids, vitamins, and polyphenols while "health benefits" refer to antioxidant, anti-obesity, and high blood pressure lowering activities. The articles that were excluded from the review were studies that (i) did not focus on *A. cruentus*, *O. gratissimum* or *S. macrocarpon*; (ii) screened polyherbal formulations; (iii) lacked information on scientific plant names; (iv) were based on ethnobotanical or ethnomedical surveys; (v) focused primarily on animal models; and (vi) were published in a language other than English or French. Hence, 296 full-text articles, judged relevant and suitable for this review, were downloaded and critically analyzed to extract data used for the review. Most of these articles focused on one of the three vegetable species (284 articles) while other articles studied two (7 articles) or three (5 articles) vegetable species.

2.3. Data retrieval

Information related to bioactive compounds and health benefits of *A. cruentus*, *O. gratissimum* and *S. macrocarpon* were extracted using Microsoft Excel 2013 spreadsheets organised per vegetable species and structured according to pre-defined variables. Data collected were

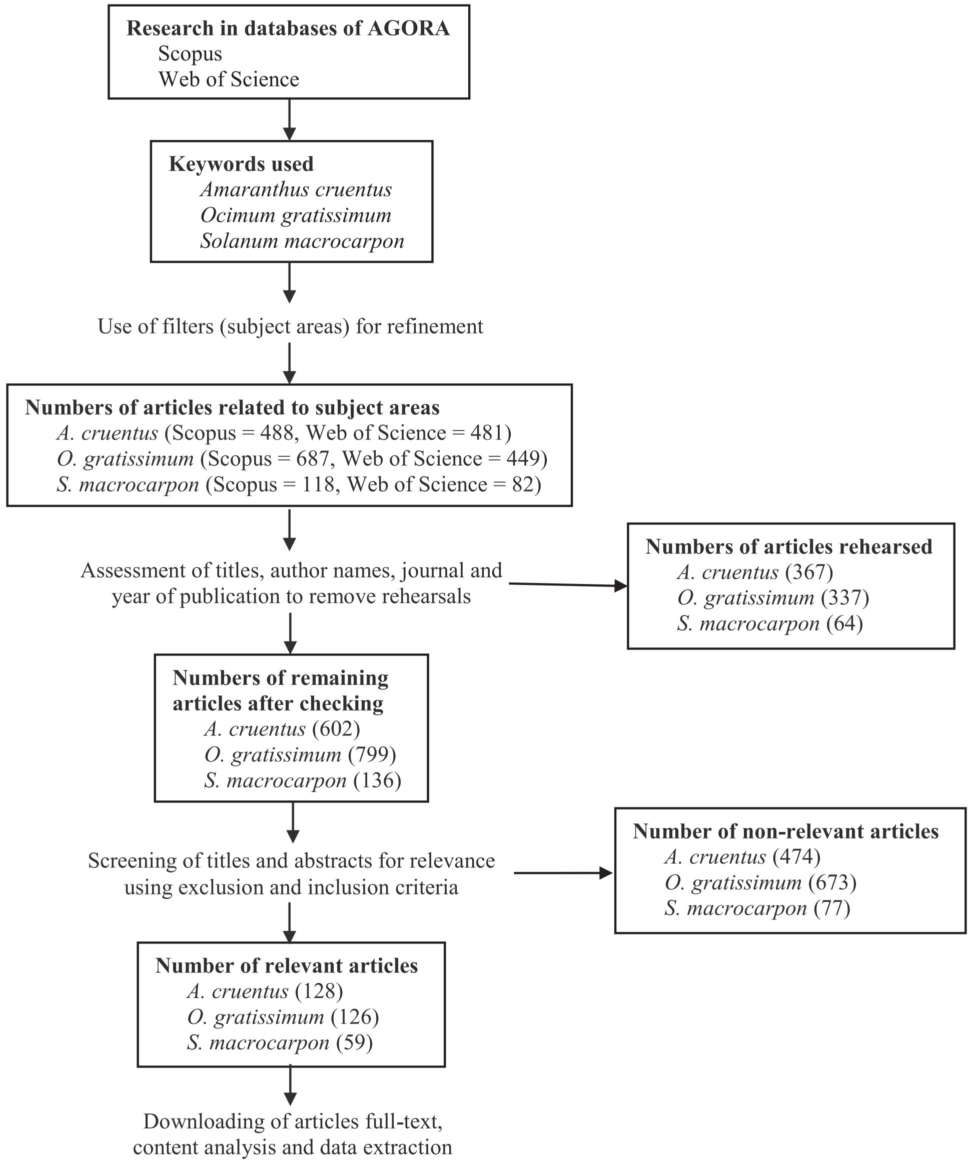

Fig. 1. Identification of articles included in the review.

related to the year of publication, the country that hosted the institution to which authors are affiliated, the plant material and their origins, the categories of bioactive compounds studied as well as the analysis methods used to determine the health-promoting properties. The missing information on detailed assay protocols were retrieved from cited references. Given that *A. cruentus*, *O. gratissimum* and *S. macrocarpon* are well-known leafy vegetables, data were collected on bioactive compounds and health-promoting properties with focus on the leaves. With respect to plant origin, publications that presented the growing conditions were screened for the use of fertilizers during plant growth and the utilized harvest times. These two factors were considered because plant nutrition is a pre-harvest factor that affects productivity and crop quality (Musa et al., 2017; Meldrum et al., 2018) while multiple harvest times performed on the same plant affect nutrient accumulation in crop's botanical parts (Awe and Osunlola, 2013; Babalola and Akinwande, 2014; Dinssa et al., 2018).

2.4. Data analysis

Basic bibliometric analysis methods were performed and the relative frequency of citation (RFC) statistic was used to evaluate scientific productivity associated with bioactive compounds and health-promoting properties of *A. cruentus*, *O. gratissimum* and *S. macrocarpon*. This statistic was calculated while dividing the relative frequency (RFi) of a particular variable (i) for one vegetable species by the total number of articles found for this vegetable species (N) using the following formula: $RFC = RF_i/N$.

3. Results

3.1. Temporal evolution and geospatial distribution of research papers

An overview of the temporal evolution of the 296 articles revealed that they were published between 1980 and 2018 while the five-year period ranking indicated a remarkable increase in publications from 2005 to 2014 (Fig. 2). Indeed, based on the five-year period ranking, research papers on these species were low (<7%) from 1980 to 2004 before it increased progressively from 2005 to 2014, irrespective of the vegetable specie (Fig. 2). From 2015–2018, which is not a full five-year period, the publication levels (*A. cruentus*: 28.9%, *O. gratissimum*: 23.8%, and *S. macrocarpon*: 25.4%) did not reach that of 2010–2014 but was above 60% of publication levels of the five-year period for *A. cruentus*

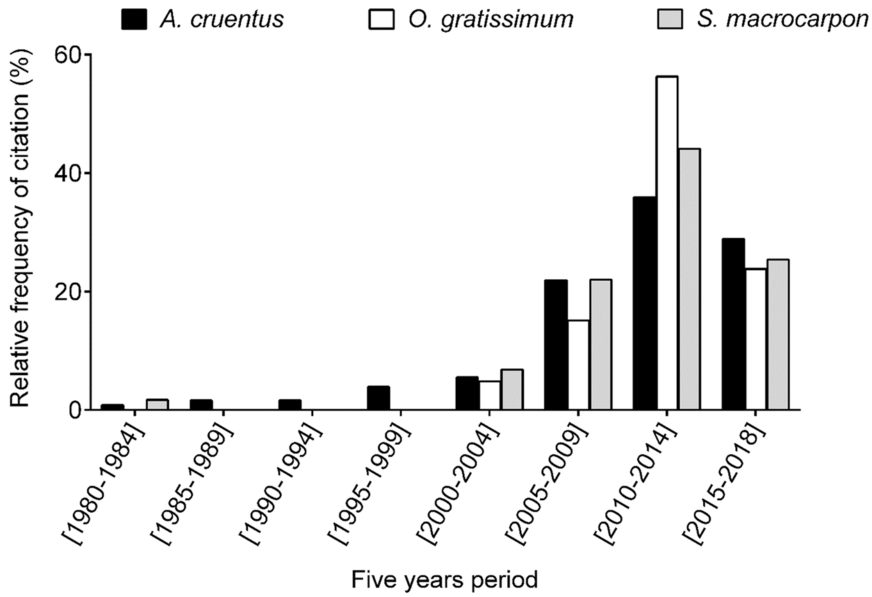

Fig. 2. Five-year period ranking of publication levels for the vegetable species.

and *S. macrocarpon* and about 40% of publication levels for *O. gratissimum* from 2010–2014 (Fig. 2). In terms of annual publication level, the highest levels of publication related to *A. cruentus* (11.7%) and *O. gratissimum* (15.9%) were in 2011 while those of *S. macrocarpon* were in 2013 and 2014 (11.9% per year). Different countries across Africa (19), the Americas (9), Asia (8), Australia, (2) and Europe (18) were involved in the publication of articles related to bioactive compounds and health-promoting properties of *A. cruentus, O. gratissimum* or *S. macrocarpon*. Most of these publications revealed co-authorship at a national level (*A. cruentus*: 74.2%, *O. gratissimum*: 80.2%, and *S. macrocarpon*: 74.6%) while the other articles indicated co-authorship at continental and international levels (Fig. 3). The co-authorship of articles at a continental level was mainly from Africa (*A. cruentus*: 52.3%, *O. gratissimum*: 68.3%, and *S. macrocarpon*: 84.7%, respectively), regardless of the vegetable species (Fig. 3). Europe and Asia were the next continents that published the most articles on *A. cruentus* (35.9%) and *O. gratissimum* (25.4%), respectively after Africa while Europe (18.6%) and America (16.9%) had comparable publication levels for *S. macrocarpon* (Fig. 3). At regional levels in Africa, most publications were from West Africa (*A. cruentus*: 29.7%, *O. gratissimum*: 61.1%, and *S. macrocarpon*: 83.1%) while at the country level, Nigeria was the major contributor to publications on bioactive compounds and health-promoting properties of *A. cruentus* (22.7%), *O. gratissimum* (55.6%) or *S. macrocarpon* (61.0%).

3.2. Plant materials used and their origins

Publications screened for this review used the plant botanical parts (seeds, leaves or fruits) and to a lesser extent, oil extracted from seeds (*A. cruentus*: 2.2%) or leaves (*O. gratissimum*: 15.7%), depending on vegetable specie (Table 1). Leaves were the predominant parts studied for *A. cruentus* (59.9%), *O. gratissimum* (84.3%) and *S. macrocarpon* (71.4%), followed by seeds for *A. cruentus* (38.0%) and fruits for *S. macrocarpon* (28.6%). The origin of most of these samples were specified in the articles related to *A. cruentus* (93.0%), *O. gratissimum* (89.8%), and *S. macrocarpon* (96.7%) although their growing conditions remain unknown (*A. cruentus*: 53.9%, *O. gratissimum*: 81.3% and *S. macrocarpon*: 76.7%) due to their reported procurement from retail

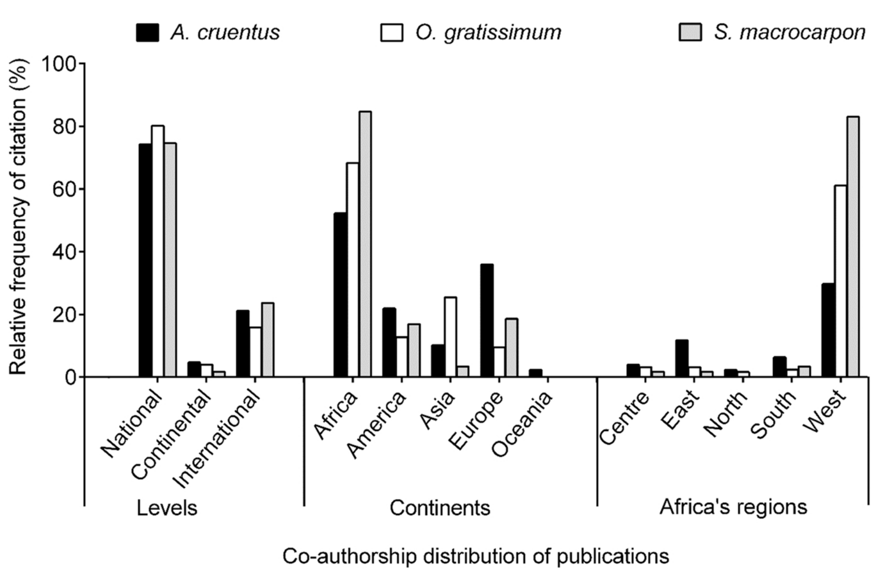

Fig. 3. Geospatial distribution of publications based on country hosting authors' institutions.

Table 1
Plant parts used as samples, their origins, and fertilizer type.

Variables		Relative frequency of citation (%)		
		Amaranthus cruentus	*Ocimum gratissimum*	*Solanum macrocarpon*
Plant material				
Botanical parts	Fruits	0.0	0.0	28.6
	Leaves	59.9	84.3	71.4
	Seeds	38.0	0.0	0.0
Derived products	Leaves oil	0.0	15.7	0.0
	Seeds oil	2.2	0.0	0.0
Origin				
Specified origin	Experimental fields	39.1	8.6	20.0
	Farmland or wild	34.4	61.7	43.3
	Retail outlets	19.5	19.5	33.3
Not specified origin		7.0	10.2	3.3
Use of fertilizers in experimental fields (%, diversity)				
Use of fertilizers		44.0	18.2	66.7
Type of fertilizers	Mineral	40.0	18.2	58.3
	Organic	16.0	9.1	50.0
	Mineral + organic	6.0	0.0	0.0
Fertilizers' diversity	Mineral	Calcium ammonium nitrate, limestone ammonium nitrate, NPK, NPK + limestone ammonium nitrate, urea, sodium selenite	Hoagland solution, hydroxyapatite, NKP, urea	NPK, NPK + ammonium sulfate, potassium chloride, sulphate of potash, urea
	Organic	broilers manure compost, cockerel manure compost, *Craseonycteris thonglongyai* droppings, crotalaria green manure, kola pod husk, layers manure compost, pacesetter's Grade B compost, pig manure, arbuscular mycorrhizal fungi + compost	cattle manure	Cattle manure, hydrolyzed fish fertilizer, Pacesetter fertilizer, broilers manure compost, providence fertilizer, rumen digesta, Sunshine Tithonia compost
	Mineral + organic	Minjingu phosphate rock + compost or crotalaria green manure, NPK + kola pod husk, NPK+ pacesetter's Grade B, NPK + pig manure or poultry manure, organic compost, manure+ calcium ammonium nitrate		NPK + farm yard manure, NPK + cattle manure

outlets, wild or farmland (Table 1). There were more samples of *A. cruentus* (39.1%) and *S. macrocarpon* (20.0%) produced in experimental fields under well-defined growing conditions than the 8.6% for *O. gratissimum* (Table 1). A diversity of fertilizers (mineral, organic, and their combination) were used in experimental fields (Table 1) with a complex of nitrogen, phosphorus and potassium (known as NPK) being the most used fertilizer (*A. cruentus*: 30.0%, *O. gratissimum*: 9.1% and *S. macrocarpon*: 41.7%).

Different harvest times were used for the botanical parts (seeds, leaves, or fruits) of *A. cruentus*, *O. gratissimum* and *S. macrocarpon* collected from experimental fields. They were expressed in number of weeks after sowing (WAS) and varied from 4–13 WAS for *O. gratissimum* (9.1%) samples, 7–13 for *S. macrocarpon* (8.3%), and 3–20 for *A. cruentus* (14.0%). However, some expressions related to a plant's age or growth stage were used to indicate harvest times of *A. cruentus* samples. For example, vegetative phase (2.0%), pre-flowering stage (4.0%), full flowering stage (4.0%), maturity stage (2.0%), full seeds development (2.0%), and reproductive phase (2.0%) were associated with the harvested leaves whereas physiological maturity or biological ripeness described seeds sampling (2.0%).

3.3. Bioactive compounds found in the leaves of the vegetable species

There were more publications on mineral profiles of *A. cruentus* (59.8%) than the polyphenols (18.5%), vitamins (29.3%), and carotenoids (28.0%). Conversely, the publication levels on polyphenols profile in *O. gratissimum* (64.7%) and *S. macrocarpon* (36.2%) leaves were higher than the minerals (31.5% and 50.0%), vitamins (18.5% and 26.1%) and carotenoids (2.8% and 8.7%), respectively. A total of thirty (30) mineral elements were determined in 21, 28, and 22 *A. cruentus*, *O. gratissimum*, and *S. macrocarpon* different leaf samples, respectively (Table 2). Calcium, magnesium, potassium, phosphorus and sodium were the major elements in *A. cruentus, O. gratissimum* and *S. macrocarpon* leaves, although the ranking order varied with the vegetable specie (Table 2). In contrast, iron, zinc, copper, and manganese were the most assessed trace elements in leaves, regardless of the vegetable specie (Table 2). Publications focusing on carotenoids evaluated the presence or absence of carotenoids, total carotenoids, and

Table 2
Mineral elements found in the leafy parts of the vegetable species.

Sub-groups	Mineral element	Relative frequency of citation (%)		
		Amaranthus cruentus	*Ocimum gratissimum*	*Solanum macrocarpon*
Major elements	Ca	63.3	73.5	82.6
	Cl	0.0	2.9	4.3
	K	67.3	64.7	73.9
	Mg	57.1	79.4	73.9
	N	18.4	14.7	8.7
	Na	38.8	52.9	65.2
	P	46.9	47.1	60.9
	S	4.1	2.9	0.0
Trace elements	Al and Sr	2.0	5.9	4.3
	As	0.0	11.8	8.7
	B	2.0	0.0	0.0
	Br	0.0	8.8	4.3
	Cd	4.1	32.4	13.0
	Co	2.0	5.9	8.7
	Cr	4.1	23.5	8.7
	Cu	34.7	67.6	47.8
	Fe	67.3	79.4	69.6
	Hg	0.0	5.9	0.0
	I, Si	0.0	2.9	0.0
	Mn	26.5	52.9	39.1
	Mo	4.1	0.0	8.7
	Ni	4.1	26.5	8.7
	Pb	4.1	26.5	26.1
	Rb, Ti and V	0.0	5.9	0.0
	Se	2.0	8.8	13.0
	Zn	55.1	76.5	60.9

different classes of carotenes and xanthophylls (Table 3). The most reported carotenoid in *A. cruentus* (73.9%) and *S. macrocarpon* (75.0%) leaves was β-carotene while total carotenoids were more determined in *O. gratissimum* (66.7%). Both fat- and water-soluble vitamins were found in the three vegetables with vitamin C being the most determined, regardless of vegetable specie and vitamin type (Table 3). Vitamins A and E were the most determined fat-soluble vitamins in the leaves of the three vegetables (Table 3).

With respect to polyphenolic compounds, phenolic acids, flavonoids, tannins, anthocyanins, and phenylpropanoids were found in the leafy vegetables (Tables 3 and 4). In general, the contents of total phenolic and total flavonoid compounds were the most used analysis methods associated with polyphenols contained in *A. cruentus* (68.0% and 44.0%), *O. gratissimum* (58.5% and 46.3%) and *S. macrocarpon* (59.1% and 27.3%) leaves (Table 3). In addition, the presence or absence of tannins and flavonoids were more screened in *O. gratissimum* (26.8% and 22.0%) and *S. macrocarpon* (22.7% and 18.2%) leaves than in *A. cruentus* (8.0% and 4.0%) leaves, respectively (Table 3). A diversity of polyphenolic compounds was found in *A. cruentus* (28.0%), *O. gratissimum* (22.0%), and *S. macrocarpon* (9.1%) leaves (Table 4). Caffeic (85.7%), coumaric (85.7%) and ferulic (85.7%) acids, as well as quercetin (100%), kaempferol (85.7%), and their derivatives were the main polyphenolic compounds determined in *A. cruentus*. Caffeic acid (70.6%), quercetin (52.9%) and their derivatives were major polyphenolic compounds found in *O. gratissimum* while for *S. macrocarpon* it was quercetin (100%) and its derivatives (Table 4). Flavanols, flavones and phenylpropanoid compounds were found in *O. gratissimum* samples only (Table 4).

3.4. Potential health-promoting properties of leaves of the vegetable species

There were many *in vitro* studies conducted on antioxidant activities of *A. cruentus* (21), *O. gratissimum* (43) and *S. macrocarpon* (18) leaves and measuring a diversity of variables for each vegetable species (Table 5). The measured variables were divided into three groups of assays: free radical scavenging, inhibition of oxidant enzymes and inhibition of oxidation (Table 5). The DPPH radical scavenging assay was the main radical scavenging assay performed on *A. cruentus* (52.4%), *O. gratissimum* (83.7%) and *S. macrocarpon* (83.3%) leaf extracts (Table 5). Superoxide dismutase, catalase and peroxidase were amongst the most determined antioxidant enzymes inhibited by *A. cruentus* (4.8%, 4.8% and 9.5%, respectively) and *O. gratissimum* (4.7%) leaves (Table 5). The inhibition of lipid peroxidation was the main assay used to evaluate the ability of *A. cruentus* (9.5%), *O. gratissimum* (23.3%) and *S. macrocarpon* (11.1%) leaves to inhibit oxidation of unsaturated fatty acids (Table 5).

Regarding other potential health benefits of these leafy vegetables, there was only one (1) *in vitro* study recorded, between 1980 and 2018 from Web of Science and Scopus collections. The work reported the inhibitory effects of *O. gratissimum* leaves on two key enzymes, i.e., pancreatic lipase and angiotensin-I converting enzyme, which are involved in the development of obesity and hypertension, respectively (Irondi et al., 2016).

4. Discussion

4.1. Evolution and worldwide distribution of scientific publications

The basic law of growth in research fields links crop importance to a higher number of publications when compared to less common and more poorly known species (Luo et al., 2018; Meldrum et al., 2018; Yeung et al., 2018). Thus, the temporal ascending trend in publication levels suggests an increased interest in bioactive compounds and potential health-promoting properties of *A. cruentus* and *O. gratissimum* at the expense of *S. macrocarpon.* The fast increase recorded after the year 2000 might have occurred owing to the increased recognition of the health-promoting properties of traditional leafy vegetables and their key role in nutrition-sensitive agriculture (Chagomoka et al., 2017; Meldrum et al., 2018). Indeed, the Green Revolution of 1960 was a calorie-centric approach that promoted the production of starchy staple foods, thereby contributing to an unhealthy diet with micronutrient insufficiencies (Meldrum et al., 2018). In such context, traditional leafy vegetables appeared as strategic assets for the reduction of the prevalence of diseases associated with malnutrition (Achikanu et al., 2013; Louis et al., 2017; Mibei et al., 2017). However, it should be noted that if the upward

Table 3
Bioactive compounds found in leafy parts of the vegetable species.

Sub-groups	Compound groups	Variables measured	Relative frequency of citation (%)		
			Amaranthus cruentus	*Ocimum gratissimum*	*Solanum macrocarpon*
Carotenoids	Carotenoids	Presence/Absence	0.0	33.3	0.0
		Total content	30.4	66.7	50.0
	Carotenes	α-carotene	4.3	0.0	25.0
		β-carotene	73.9	0.0	75.0
		Lycopene	4.3	0.0	0.0
	Xanthophylls	β-cryptoxanthin	4.3	0.0	0.0
		Lutein	21.7	0.0	50.0
		Neoxanthin	4.3	0.0	25.0
		Violaxanthin	8.7	0.0	25.0
		zeaxanthin	8.7	0.0	50.0
Vitamins	Fat-soluble	Vitamin A	16.7	5.0	25.0
		Vitamin E	8.3	10.0	33.3
		Vitamin K1	0.0	0.0	8.3
	Water-soluble	Vitamin B1	4.2	25.0	0.0
		Vitamin B2	4.2	25.0	0.0
		Vitamin B3	0.0	30.0	0.0
		Vitamin B6	0.0	5.0	0.0
		Vitamin C	91.7	95.0	83.3
Polyphenols	Anthocyanin	Presence/Absence	0.0	3.7	4.5
		Total content	8.0	3.7	4.5
	Flavonoids	Presence/Absence	4.0	22.0	18.2
		Total content	44.0	46.3	27.3
	Phenolics	Presence/Absence	0.0	9.8	0.0
		Total content	68.0	58.5	59.1
	Tannin	Presence/Absence	8.0	26.8	22.7
		Total content	8.0	19.5	18.2

Table 4
Polyphenolic compounds found in leafy parts of the vegetable species.

Sub-classes	Compound groups	*Amaranthus cruentus*		*Ocimum gratissimum*		*Solanum macrocarpon*	
		RFC (%)	Compounds	RFC (%)	Compounds	RFC (%)	Compounds
Flavonoids							
Flavanols	Catechin and its derivatives	0.0		5.9	Catechin; Epicatechin	0.0	
Flavones	Acacetin	0.0		5.9	Acacetin	0.0	
	Apigenin and its derivatives	0.0		47.1	Apigenin; Apigenin 5-O-glucoside; Apigenin 7,4,′-dimethyl ether; Apigenin 7-O-glucoside; Apigenin 7-O-glucuronide; Apigenin 7-O-malonylglucoside; Apigenin-7-O-rutinoside; Vicenin-2; Vitexin; Isovitexin	0.0	
	Cirsiliol	0.0		11.8	Cirsiliol	0.0	
	Cirsilineol	0.0		5.9	Cirsilineol	0.0	
	Cirsimaritin	0.0		29.4	Cirsimaritin	0.0	
	Gardenin B	0.0		5.9	Gardenin B	0.0	
	Hymenoxin	0.0		5.9	Hymenoxin	0.0	
	Isothymusin	0.0		11.8	Isothymusin	0.0	
	Luteolin and its derivatives	0.0		47.1	Luteolin; Luteolin 5-O-glucoside; Luteolin 7-O-glucoside; Luteolin 7-O-glucuronide; Orientin; Isoorientin	0.0	
	Nevadensin	0.0		29.4	Nevadensin	0.0	
	Sinensetin derivatives	0.0		5.9	5-Desmethylsinensetin	0.0	
	Salvigenin	0.0		17.6	salvigenin	0.0	
	Xanthomicrol	0.0		11.8	Xanthomicrol	0.0	
Flavonols	Kaempferol and its derivatives	85.7	Nicotiflorin	47.1	Kaempferol; Kaempferide; Kaempferol 3-O-malonylglucoside; Nicotiflorin	50.0	Nicotiflorin
	Myricetin	0.0		0.0		50.0	Myricetin
	Quercetin and its derivatives	100	Quercetin; Isoquercitin; Quercetin 3-neohesperidoside; Quercetin 3-rutinoside-7-rhamnoside; Quercetin 7-rutinoside; Quercetin-rhamnoglucorhamnoside; Rutin	52.9	Quercetin; Isoquercitin; Quercetin 3,4′-diglucoside; Quercetin 3-O-(6-O-malonyl)glucoside; Quercetin 3-O-malonylglucoside; Quercetin 3-O-xylosyl(1→2) galactoside; Quercitrin; Rutin	100	Rutin
Phenolic acids							
Hydroxybenzoic acids	Ellagic acid	14.3	Ellagic acid	5.9	Ellagic acid	0.0	
	Gallic acid and its derivatives	14.3	Gallic acid	17.6	Gallic acid; Galloylglucose; Methyl gallate	50.0	Gallic acid
	Gentistic acid	14.3	Gentistic acid	0.0		0.0	
	Hydroxybenzoic acid and its derivatives	28.6	Hydroxybenzoic acid; 2,4-dihydroxybenzoic acid	5.9	p-hydroxybenzoic acid	0.0	
	Protocatechuic acid and its derivatives	14.3	Protocatechuic acid	11.8	Protocatechuic acid; Ethyl protocatechuate; Methyl protocatechuate	0.0	
	Salicylic acid	14.3	Salicylic acid	0.0		0.0	
	Syringic acid	28.6	Syringic acid	5.9	Syringic acid	0.0	
	Vanillic acid	14.3	Vanillic acid	5.9	Vanillic acid	0.0	
Hydroxycinnamic acids	Caffeic acid and its derivatives	71.4	Caffeic acid; Caffeoylaldaric acid esters; Caffeoylglucaric isomer 1–6; Caffeoyl isocitrat isomer 1–2; Caffeoylisocitric acid esters	70.6	Caffeic acid, Caftaric acid; L-caftaric acid;Nepetoidin A; Rosmarinic acid; Verbascoside; Ethyl caffeate; Caffeoyl derivatives	50.0	Caffeic aicd
	Cichoric acid and its derivatives	0.0		11.8	Cichoric acid;	0.0	
	Chlorogenic acid and its derivatives	0.0		17.6	Chlorogenic acid	50.0	Chlorogenic acid derivative
	Cinnamic acid and its derivatives	0.0		0.0		50.0	Cynnamoyl derivative
	Coumaric acid and its derivatives	85.7	Coumaric acid, p-Coumaric acid, Coumaroylglucaric isomer 1–5, Coumaroylisocitric acid esters	5.9	p-Coumaric acid	0.0	
	Ferulic acid and its derivatives	85.7	Ferulic acid; Feruloylaldaric acid esters; Feruloylglucaric isomer 1–6; Feruloyl isocitrat isomer 1–2; Feruloylisocitric acid esters	17.6	Ferulic acid; trans-ferulic acid	0.0	
	Sinapic acid	14.3	Sinapic acid	17.6	Sinapic acid	0.0	
Phenylpropanoids	Coniferaldehyde	0.0		5.9	Coniferaldehyde	0.0	
	Eugenol and its derivatives	0.0		35.3	Eugenol; Methoxyeugenol; Methyl eugenol	0.0	

Table 5
Functional properties of the leafy parts of vegetable species.

Properties		Variables measured	Relative frequency of citation (%)		
			Amaranthus cruentus	*Ocimum gratissimum*	*Solanum macrocarpon*
Antioxidant activities	Free radical scavenging assays	ABTS	28.6	32.6	11.1
		DPPH	52.4	83.7	83.3
		Ferrous ion chelation	4.8	16.3	11.1
		Hydroxyl radical	0.0	20.9	0.0
		Hydrogen peroxide radical	0.0	4.7	0.0
		Nitric oxide radical	0.0	11.6	0.0
		Oxygen radical absorption capacity	14.3	2.3	0.0
		Reducing power	42.9	46.5	55.6
		Superoxide radical	0.0	7.0	0.0
	Enzyme assays	Catalase	4.8	4.7	0.0
		Glutathione S-transferase	0.0	2.3	0.0
		Lipoxygenase	0.0	2.3	0.0
		Peroxidase	9.5	4.7	0.0
		Superoxide dismutase	4.8	4.7	0.0
		Xanthine oxidase	4.8	0.0	0.0
	Inhibition of oxidation assays	β-carotene-linoleic acid bleaching	0.0	4.7	0.0
		Hydrogen peroxide generation	0.0	2.3	0.0
		Inhibition of lipids peroxidation	9.5	23.3	11.1
		Reduced glutathione level	0.0	2.3	0.0
		Inhibition of ascorbic acid oxidation	4.8	4.7	16.7
High blood pressure lowering activities	Enzyme assays	Angiotensin-I converting enzyme inhibition	0.0	100	0.0
Anti-obesity	Enzyme assays	Inhibition of pancreatic lipase activity	0.0	100	0.0

trend continues as experienced in 2015–2018, it can be assumed that the publication levels may reach or be higher than that of the 2010–2014 from 2019 onwards.

The studied leafy vegetables are commonly found in the tropical and sub-tropical non-arid regions while *A. cruentus* occurs also in temperate regions (Musa et al., 2011). Thus, the predominance of publications in Africa and particularly in West Africa are likely to be predicated considering that traditional leafy vegetables are indispensable components of African diets and cultural heritage (Achikanu et al., 2013; Adedokun et al., 2016). In addition, leafy vegetables are generally used for food and medicine in many countries of the world, especially in eastern, central, southern and western regions of Africa (Achigan-Dako et al., 2010; Chagomoka et al., 2017; Nyathi et al., 2019). Geographic proximity could facilitate collaboration between researchers and may explain why most co-authorship were at the national level. Considering that international collaboration is an important tool for finding common patterns and solutions to the same problems across a wide spatial scale (Luo et al., 2018; Meldrum et al., 2018; Yeung et al., 2018), the globalization of science and technology could be a key factor contributing to co-authorships between researchers (at the country, continent and global levels). Thus, a high prevalence of collaboration between researchers working in neighboring and distant countries may be recorded in the future.

4.2. Origin of plant materials

Leaves are the most consumed part of *A. cruentus*, *O. gratissimum* and *S. macrocarpon* (Biel et al., 2017) and this may explain why most of the publications focusing on their bioactive compounds and health-promoting properties were based on their leafy parts. In addition, *A. cruentus* seeds are used in formulation of food for humans and feed for animals in America, Asia and Europe (Biel et al., 2017) while *S. macrocarpon* fruit is important to people in West Africa and Southeast Asia (Staley et al., 2013). Therefore, the importance and the use of the botanical parts of these species depend on geographical areas and similar trends could be expected for their derived-products (e.g., *A. cruentus* seeds oil and *O. gratissimum* leaves oil). In Africa, most traditional leafy vegetables are part of naturally grown food resources although they have the potential to be cultivated crops (Akanbi et al., 2010; Musa et al., 2017). The availability of these plant resources may explain why samples of *A. cruentus*, *O. gratissimum* and *S. macrocarpon* used were purchased at retail outlets, and collected from the wild or farmland (Akanbi et al., 2010; Musa et al., 2017). However, the availability of traditional leafy vegetables can decline due to excessive collection from the wild (Babalola and Akinwande, 2014), which leads to renewed interest in the cultivation of these plant resources. Given that many traditional leafy vegetables are able to grow on poor soils and under water-limited conditions, various approaches were used to promote the production and consumption of these nutritious and health-promoting foods (Chagomoka et al., 2017; Meldrum et al., 2018). The cultivation of traditional leafy vegetables is associated with important agronomic challenges (especially those related to soil fertility, water availability, pest and disease control) that have steadily increased due to climate change and the need to protect human and environmental health (Meldrum et al., 2018). Thus, more attention should be paid to plant growing conditions in order to clarify the complex relationships between soil quality, water availability and nutrient contents, which all depend on the vegetable specie.

4.2.1. Use of fertilizers for plant growth

Fertilizers are the major sources of plant nutrients and the most important and controllable factor affecting the nutritional value of leafy vegetables (Musa et al., 2017). Consistent, with previous studies, we found that inorganic, organic and a combination of both types of fertilizers were used to improve soil fertility although the type and level of application were reported to directly influence the concentrations of nutrients available for plant growth and development (Adekayode and Ogunkoya, 2011; Makinde, 2012; Musa et al., 2017). Organic fertilizers (manures, leaves, and compost) are animal- or plant-based materials that are either by-products or end-products of naturally occurring processes (Staley et al., 2013; Dada et al., 2017; Musa et al., 2017). They were reported to enhance soil water holding capacity and growth of microorganisms that reconditioned the soil, thereby ensuring slow release of needed nutrients for plant growth (Adekayode and Ogunkoya, 2011; Staley et al., 2013; Dada et al., 2017; Musa et al., 2017). Organic fertilizers are characterized by low contents of nutrients, meaning that high amounts are needed to provide sufficient nutrients for crop growth while the need for decomposition of organic fertilizers delays nutrients availability for plants (Adekayode and Ogunkoya, 2011).

In contrast, inorganic fertilizers are synthetic chemicals (either granular or liquid) that contain macronutrients needed in large amounts by plants (nitrogen, phosphorous and potassium) and in readily available forms, which influence vegetative and reproductive phases of plant growth (Musa et al., 2011; Dada et al., 2017). This may explain why inorganic fertilizers are preferred to organic fertilizers for production of leafy vegetables and why NPK is the most used inorganic fertilizer for field experimentation. However, it should be noted that if these three macronutrients are not available in adequate amounts in the soil, they could be a limiting factor for plant growth and development. Nitrogen is undeniably very important for growth of stems and leaves in vegetables production while phosphorus and potassium are involved in regulation of metabolism, flowering and fruiting processes (Musa et al., 2011; Dada et al., 2017). Inorganic fertilizers are soluble and immediately available to plants with high nutrient contents. Thus, relatively small amounts would be required for the crop growth while their overuse may induce environmental pollution through leaching of nutrients into water with potential hazards to animals and humans (Akanbi et al., 2010; Adekayode and Ogunkoya, 2011; Makinde, 2012; Musa et al., 2017).

The use of only one type of fertilizer may not supply adequate amounts of nutrients over time, thus, requiring the combination of slow (organic) and fast (inorganic) acting fertilizers in order to induce a quick boost of nutrients that will continue throughout the plant growth stages (Makinde, 2012; Okebalama et al., 2017; Tovihoudji et al., 2017). The traditional method of inorganic fertilizer application is broadcasting over the soil without consideration for environmental consequences (Okebalama et al., 2017; Tovihoudji et al., 2017). As an alternative method, fertilizer micro-dosing has been promoted as a precision application method to ensure appropriate and balanced levels of organic and/or inorganic fertilizers in the soil (Okebalama et al., 2017; Tovihoudji et al., 2017). This fertilization system could be considered environmentally friendly because of the reduction in chemical fertilization and its combination with organic fertilizers.

4.2.2. *Maturity of plant materials at harvest time*

In general, during their life, plants go from seeds to sprout, then through vegetative, budding, flowering, fruiting, ripening, and seed development stages. Hence, depending on the targeted botanical parts (leaves, fruits or seeds), wide variations in harvest time may occur since the time needed for seed development is longer than that needed for fruiting, which is in turn longer than that needed for vegetative growth. Thus, wide variations in the ranges of harvest time (expressed in weeks or months) were expected due to the fact that different plant botanical parts were considered. For leafy vegetables, farmers usually perform multiple harvests by cutting the central stem at 10 cm from its base during stem elongation or by pinching leaves, tender branches, and shoots (Awe and Osunlola, 2013; Babalola and Akinwande, 2014; Dinssa et al., 2018) instead of the unique harvest of uprooting the plant (Dinssa et al., 2018). The pinching method allows the central stems to flower and produce seeds (Babalola and Akinwande, 2014; Dinssa et al., 2018), while the cutting method delays floral initiation, enhances branching and leaf development, thereby increasing biomass yield and farmers' income (Awe and Osunlola, 2013; Babalola and Akinwande, 2014). The choice of the best time for harvest is determined by choosing a specific day after sowing or by following the plant's development phase (Biel et al., 2017). Regardless of the harvest time, the end of vegetative stage was reported to be an appropriate harvest period for high nutritional value and digestibility of the plant tissues while the full bloom stage was associated with high biomass yield (Biel et al., 2017). Hence, harvest time of plant materials may contribute to their bioactive compounds and health-promoting properties according to environmental and growth conditions.

4.3. *Leafy vegetables as sources of bioactive compounds*

The bioactive compounds of interest in this review cannot be synthesized in the human body to a large extent and must be supplied through diet. Plants get water and minerals from soil and irrigation systems (Achikanu et al., 2013; Ogoko, 2015; Louis et al., 2017), although their ability to take up and accumulate minerals differs widely among cultivars and varieties within the same species (Louis et al., 2017). In contrast, carotenoids, vitamins, and polyphenolic compounds are synthesized by plants (Osuagwu et al., 2010; Steiner-Asiedu et al., 2014).

4.3.1. *Diversity and importance of minerals found in the leafy vegetables*

Minerals play an important role in the proper functioning and general well-being of the human body by working in synergy with vitamins, enzymes and co-enzymes to keep the body in a balanced working order (Ogoko, 2015; Tripathi et al., 2015). Minerals are classified into major and trace elements depending on the amount needed by the human body. The body also depends on the supply of essential minerals for proper physiological functioning (Ogoko, 2015). It has been recognized that proper intake of some major minerals (calcium, phosphorus, potassium, magnesium and sodium) decrease the risks associated with various human diseases to a large extent (Tripathi et al., 2015; Ogbuji et al., 2016). This may explain why these elements are frequently determined in the leafy vegetables. Some trace elements including chloride, cobalt, copper, iodine, iron, manganese and zinc were reported to have a specific biochemical functions in plants and the human body, which make them essential for the growth and life of plants, animals and humans (Tripathi et al., 2015; Adedokun et al., 2016). This may explain why iron, zinc, copper, and manganese are among the most frequently determined trace elements in *A. cruentus, O. gratissimum* and *S. macrocarpon* leaves. The trace elements with a specific gravity of at least five times that of water at 4 °C (e.g., aluminum, arsenic, cadmium, chromium, copper, iron, lead, manganese, mercury, nickel and zinc) are considered heavy metals (Ogoko, 2015; Adedokun et al., 2016; Ogbuji et al., 2016). Thus, there are some heavy metals that are useful for the human body while others such as aluminum, arsenic, cadmium, lead, and mercury are not essential and are considered toxic due to their short and long-term hazardous effects in plants, animals, and humans (Ogoko, 2015; Ogbuji et al., 2016).

4.3.2. *Diversity and functions of carotenoids and vitamins found in the leafy vegetables*

Carotenoids are the most widespread natural color pigments in plants and they act as accessory pigments for photosynthesis and as precursors to plant hormones while imparting various benefits to human health (Steiner-Asiedu et al., 2014; Mibei et al., 2017). They are particularly important because of their roles as antioxidants and vitamin A precursors (Steiner-Asiedu et al., 2014; Nyathi et al., 2019). The biological functions of carotenoids and vitamin A in humans are associated with normal vision, gene expression, growth, cell differentiation, immune function through maintenance of epithelial cell functions, and other physiological processes (Osuagwu et al., 2010; Achikanu et al., 2013; Steiner-Asiedu et al., 2014; Nyathi et al., 2019). The most common carotenoids included in the human diet is β-carotene, followed by α-carotene, β-cryptoxanthin, lutein, zeaxanthin, and lycopene (Steiner-Asiedu et al., 2014; Nyathi et al., 2019), which is consistent with our findings for levels of publications on these bioactive compounds. The human body is able to convert water-soluble carotenoids (α-carotene, β-carotene, and β-cryptoxanthin) into vitamin A (Steiner-Asiedu et al., 2014; Nyathi et al., 2019) while the main function of lipid-soluble carotenoids (zeaxanthin and lutein) is to maintain normal vision of the eye macula (Steiner-Asiedu et al., 2014).

The importance of vitamin C in the normal functioning of human body may explain the high levels of publications recorded. Vitamin C is essential for humans because of its key role in the formation of intercellular substances, transport and uptake of non-heme iron at the mucosa, reduction of folic acid intermediates, synthesis of cortisol and collagen, normal wounds healing and transformation of cholesterol into bile acid in the liver (Osuagwu et al., 2010; Achikanu et al., 2013). Its deficiency leads to the fragility of the endothelial wall of blood capillaries, scurvy, and hyperkeratosis (Osuagwu et al., 2010; Achikanu et al., 2013). Vitamin B1, B2 and B3 were the most determined among the B complex (especially in *O. gratissimum* leaves) possibly because of their role in the prevention of beriberi disease (vitamin B1), skin and eye disorders (vitamin B2), pellagra disease (vitamin B3), and energy release from food during breathing (vitamin B2) (Osuagwu et al., 2010). All the above mentioned are related to malnutrition and unbalanced diets. Vitamin E was the least studied as it exists in eight different forms (α-, β-, γ-, δ-tocopherols and α-, β-, γ-, δ-tocotrienols) among which only α-tocopherol is the most active form in the human body with a key role in the formation and normal functioning of red blood cell and muscles (Achikanu et al., 2013).

4.3.3. Diversity and functions of polyphenols found in the leafy vegetables

Polyphenolic compounds are secondary metabolites that are important for plants' normal growth, development, and defense against pathogens, herbivore predators, infections, and injury (Salawu et al., 2013; Ayodele et al., 2015). Most of them are synthesized by the phenylpropanoid pathway while others (e.g., caffeic acid) are produced by the shikimate biosynthetic pathway (Ayodele et al., 2015; Jyotshna et al., 2018). Polyphenols have a wide spectrum of biological and pharmacological effects, which contribute to their health benefits widely recognized in many epidemiological studies (Guerrero et al., 2012; Salawu et al., 2013). As recorded in this review, there is a great diversity of polyphenolic compounds classified into phenolic acids (hydroxybenzoic acids, hydroxycinnamic acids and glycosidic phenylpropanoids); flavonoids (anthocyanins, anthoxanthins, flavanols, flavonols, flavones, flavonones, etc.), and non-flavonoids (tannins) compounds (Guerrero et al., 2012; Ayodele et al., 2015; Louis et al., 2017). This classification depends on the structure, number, and position of phenolic hydroxyl groups or oxygenated heterocycles that exist within the skeleton of polyphenolic compounds (Guerrero et al., 2012; Ayodele et al., 2015; Louis et al., 2017). This review revealed that the qualitative profile of polyphenolic compounds in *A. cruentus, O. gratissimum* and *S. macrocarpon* leaves varied with vegetable species and classes or sub-classes of polyphenolic compounds. This suggests that polyphenolic composition and type of compounds might contribute to some of the differences in functional properties of the *A. cruentus, O. gratissimum* and *S. macrocarpon* leaves. For example, rosmarinic acid showed anti-mutagen, antibacterial, anti-viral and high blood glucose lowering properties (Jyotshna et al., 2018) while rutin exhibited cardioprotective, anti-arthritic anti-cancer and high blood lipids and pressure lowering activities (Guerrero et al., 2012; Jyotshna et al., 2018).

4.4. Mechanisms associated with the functional properties of the leafy vegetables

The three leafy vegetables species are reputed to promote health by managing oxidative stress- and age-related diseases as well as cardiovascular and neurodegenerative diseases (Grubben and Denton, 2004; Dansi et al., 2008; Achigan-Dako et al., 2010, 2014). The key role of oxidative stress in the etiology of many age-related, chronic, cardiovascular, and neuro-degenerative disease conditions (Irondi et al., 2016) could explain why more publications investigated the antioxidant activity of the three leafy vegetable species than their anti-hypertension and anti-obesity properties. In folk medicine, *A. cruentus* is used to treat fever, stomach aches, constipation, diarrhoea, dysentery, liver infections, knee pain, hemorrhage, anemia and kidney malfunctions (Grubben and Denton, 2004; Dansi et al., 2008; Achigan-Dako et al., 2010, 2014). In contrast, *O. gratissimum* and *S. macrocarpon* leaves are used in traditional medicine practices for weight reduction and treatment of diabetes and obesity (Grubben and Denton, 2004; Dansi et al., 2008). Thus, the use of *A. cruentus* leaves to prevent or treat oxidative stress-related diseases is not common and could be linked to the low relative frequency of publications on its antioxidant activities and consequently to the scant number of publications related to its anti-hypertensive, anti-obesity and anti-diabetic properties.

Pharmacological potentials of the studied vegetable species are attributed in part to carotenoids, vitamins and polyphenols, which act through various mechanisms to prevent oxidative stress-related diseases including obesity, diabetes, and hypertension (Irondi et al., 2016). Polyphenols, carotenoids, vitamin A, C, and E were reported to be powerful biological antioxidants that are able to protect cells from oxidative damage, thereby preventing oxidative stress-related diseases in the human body (Osuagwu et al., 2010; Guerrero et al., 2012; Salawu et al., 2013; Louis et al., 2017; Mibei et al., 2017; Jyotshna et al., 2018). Therefore, the fact that more attention was paid to the health-promoting properties of *O. gratissimum* and *S. macrocarpon* leaves could be related to the high levels of publication found for their carotenoids and polyphenol profiles when compared to that of *A. cruentus* (Table 3). Likewise, there were more research works that profiled vitamin C in *O. gratissimum* leaves and vitamins A and E in *S. macrocarpon* leaves (Table 3). Oxidation of various biomolecules (nucleic acids, glucosides, lipids and proteins) resulting from excessive oxidative stress is an etiological factor involved in many age-related and chronic disease conditions. Thus, minimizing oxidative stress could prevent many related diseases and may explain why some publications focused on antioxidant properties of *A. cruentus, O. gratissimum* and *S. macrocarpon* leaves rather than their blood glucose, lipids and blood pressure lowering activities.

4.4.1. Antioxidant properties of the leafy vegetables

Free radicals and reactive oxygen species are continuously generated during physiological processes in the human body and their overproduction beyond the capacity of the naturally available antioxidant defense system leads to oxidative stress. Antioxidant compounds prevent oxidative damage by scavenging free radicals, chelating catalytic metals and inhibiting lipid peroxidation (Ademoyegun et al., 2013; Granato et al., 2018). They also act as reducing agents with the ability to protonate oxidizing agents (e.g., hydroxyl radical) or to transfer electron or hydrogen atom to oxidants or free radicals (Ademoyegun et al., 2013; Granato et al., 2018). As recorded in this review, the assays based on DPPH radical, ABTS radical, oxygen radical, and ferric ion reducing antioxidant power were reported to be the most frequently used antioxidant methods (Granato et al., 2018). Moreover, enzyme- and cell-based *in vitro* antioxidant assays are also used to assess the antioxidant properties (Ademoyegun et al., 2013; Granato et al., 2018). The diversity of antioxidant mechanisms could provide important information on the structure-activity relationships governing antioxidant properties of *A. cruentus, O. gratissimum* and *S. macrocarpon* leaves.

4.4.2. Blood pressure-lowering properties of the leafy vegetables

Hypertension is one of the strongest cardiovascular risk indicators characterized by a persistent elevation of systemic arterial pressure above systolic and diastolic blood pressure ratio of 140/90 mmHg (Irondi et al., 2016). Hence, systolic and diastolic blood pressure are key indicators of hypertension and they can only be measured through animal-based studies. Blood pressure regulation is based on the activation of the renin-angiotensin system with successive conversions of angiotensinogen into active angiotensin-I by renin and of angiotensin-I into angiotensin-II by angiotensin-I converting enzyme (Irondi et al., 2016). Angiotensin II stimulates vasoconstriction, increases sodium and water reabsorption, and elevates blood pressure (Irondi et al., 2016). Moreover, angiotensin II induces oxidative stress, which plays a key role in the development of hypertension (Irondi et al., 2016). Thus, the etiology of hypertension is associated with angiotensin-I converting enzyme activity, which also degrades bradykinin, a blood pressure-lowering vasodilator (Irondi et al., 2016). Consequently, angiotensin-I converting enzyme inhibitors are widely used in the treatment of hypertension and cardiovascular diseases (Irondi et al., 2016). Furthermore, this review indicated that angiotensin-I converting enzyme inhibition was the most frequently used assay to determine potential high blood pressure-lowering activity of *O. gratissimum* leaves.

4.4.3. High blood lipids lowering properties of leafy vegetables

High blood lipids result from elevated levels of triglycerides, low-density lipoproteins, and very low-density lipoproteins cholesterol and low level of high-density lipoproteins cholesterol in the blood. An increase in body fat and weight accumulation lead to an overweight, which is often related to obesity, and a subsequent increase in the incidence of hypertension, diabetes, atherosclerosis, and cardiovascular diseases. Pancreatic lipase, the key enzyme involved in lipids metabolism, hydrolyzes triglycerides to produce glycerol and fatty acids, thereby increasing absorption of triglycerides, body fat accumulation, weight gain, and the incidence of obesity (Irondi et al., 2016). Therefore, inhibition of pancreatic lipase is widely used as an index in the evaluation of the potential efficacy of anti-obesity agents: case of *O. gratissimum* leaves (Irondi et al., 2016).

Considering that vegetable oils contribute to lower blood lipids (Biel et al., 2017), the fact that *O. gratissimum* leaves contain an essential oil (Ayodele et al., 2015) could have promoted research works on its high blood lipid and blood pressure-lowering abilities. Besides, blood lipid levels are positively correlated to the occurrence of diseases associated with damages to the coronary artery, which can induce hypertension (Irondi et al., 2016). In addition, activation of the renin-angiotensin system enzymes was reported as one of the possible mechanisms by which obesity contributes to hypertension (Irondi et al., 2016). Hence, systemic oxidative stress is a common feature of obesity and its related hypertension while overweight and obesity are common issues associated with disturbance in carbohydrates and lipids metabolism resulting from excessive intake of carbohydrates and lipids (Irondi et al., 2016). Therefore, research into leafy vegetables that inhibit activities of key enzymes involved in high blood glucose, lipids and pressure could be beneficial for a better understanding of the effectiveness of these vegetables in the treatment of obesity, hypertension and diabetes.

4.5. Limitations of the review

This review presented temporal and geospatial distributions of the publications related to bioactive compounds and health-promoting properties of *A. cruentus*, *O. gratissimum* and *S. macrocarpon.* Some limitations to this review are related to the keywords used for the search of the articles, which can directly affect the results. It is important to note that the consulted databases could introduce further limitations by not yielding exhaustive literature articles that report the bioactive compounds and health-promoting properties of interest. Although the selected databases include most articles that are also considered by other repositories, the results might have been different if we had worked with another combination of databases. The approach used in this work was intended to be a qualitative profiling of bioactive compounds, thereby excluding a quantitative review although the work can be completed with a quantitative study. Likewise, the understanding of the term “health-promoting” could be extended to other properties associated with oxidative stress-related diseases like anti-inflammatory and hepatoprotective activities in order to get more information on the ability of the studied leafy vegetables to prevent oxidative stress-related diseases.

4.6. Gaps in the scientific literature

This review identified several gaps in the scientific literature, despite the emerging focus on some bioactive compounds and health-promoting properties of *A. cruentus*, *O. gratissimum* and *S. macrocarpon*. It also revealed some critical research gaps on plant growing conditions and this may affect tracking of the bioactive compounds and health-promoting profiles attributed to the vegetable species. Prior to analysis, vegetable samples were subjected to various pre- and post-harvest treatments, which all together contributed to the results (either qualitative or quantitative) reported in the literature. For example, polyphenolic compounds identified or not depending on the vegetable species could result from such variations. There is a general lack of research focusing on the extent of high blood glucose, lipids, and pressure-lowering activities of *A. cruentus* while there is little information regarding these health-promoting properties for *O. gratissimum* and *S. macrocarpon*. Most assays used in determining the potential health-promoting properties were *in vitro* methods. Thus, the reported health-promoting properties remain theoretical due to a lack of information on their effectiveness in animal models, especially the human body.

5. Conclusion

A bibliometric study coupled with content analysis gave the overall structure of the scientific literature on bioactive compounds and health-promoting properties of *A. cruentus*, *O. gratissimum,* and *S. macrocarpon*. Over the past 40 years, literature articles focused more on *O. gratissimum* and *A. cruentus* than on *S. macrocarpon* while West Africa remained the region from where most of the research were conducted. Sample origins were variable, ranging from purchases at retail outlets to those harvested in the wild or farmland. Minerals, carotenoids, vitamins, and polyphenols contained in these leafy vegetables were profiled and the various mechanisms by which the leaf extracts exert their antioxidant activities as well as lowering of blood lipids and pressure were established. Both *A. cruentus* and *S. macrocarpon* have great potential as functional ingredients although more attention has been paid to *O. gratissimum* leaves. Therefore, the exploration of bioactive compounds and health-promoting properties of *A. cruentus*, *O. gratissimum,* and *S. macrocarpon* produced in well-defined growing conditions may be a major challenge for global academic research. Optimization of plant growing conditions is needed and must take into account crop productivity, environment, and human health as well as food and nutritional security. Such optimization may be achieved by using an environmentally friendly and climate-smart technology such as fertilizer micro-dosing, which improves soil fertility and crop productivity with limited resources, thereby increasing farmers’ income. Then, it would be interesting to assess the effect of fertilizer micro-dosing on the nutritional and health-promoting properties of these leafy vegetables. Literature indicated that leaves’ bioactive compounds and health-promoting properties were influenced by plants’ growth conditions and leaf maturity stage at harvest time. Hence, considering that farmers usually perform multiple harvests, it would be of great interest to assess the effect of this practice on the nutritional and health-promoting properties of leafy vegetables cultivated with fertilizer micro-dosing.

Ethical consideration

Ethics approval was not required for this research.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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