Crop Protection 174 (2023) 106423

Contents lists available at ScienceDirect

Crop Protection

journal homepage: www.elsevier.com/locate/cropro

An appraisal on the ethnobotany and antimicrobial activity of botanicals used for managing plant diseases in South Africa

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ARTICLE INFO

Keywords:
Antifungal
Antibacterial
Biotic stress
Food security
Phytopathogens
Plant diseases

ABSTRACT

Increased food insecurity caused by factors such as plant pests and pathogens has prompted the use of botanicals as alternative control agents. In this review, the ethnobotany and antimicrobial effect of botanicals used for the management of plant diseases in South Africa were critically assessed. Electronic databases were accessed for relevant scientific literature that met the inclusion criteria. The systematic assessment yielded 16 studies that generated an inventory of 66 plant species (44 families) that are used in managing microbial-related plant diseases. The dominant plant families were Fabaceae and Solanaceae with each represented by five plant species. Antifungal activity was the only assay-type recorded for evaluating the plant species while the microplate dilution method (62.5%) was the most used technique. The leaves (87%) were the most common plant part that have been evaluated for antifungal activity, while acetone (69%) was the most popular solvent used for extracting the plant materials. Approximately 80% of the screened plants demonstrated promising antifungal activity against phytopathogens. For instance, the acetone extract of *Breonadia salicina* leaves had significant antifungal activity against *Penicillium janthinellum* (Minimum Inhibitory Concentration, MIC = 0.08 mg/ml), while the acetone extract of *Markhamia obtusifolia* leaves displayed strong antifungal activity against *Aspergillus flavus* (MIC of 0.08 mg/ml) and *Fusarium verticilloides* (MIC of = 0.08 mg/ml). *Breonadia salicina*, *Harpephyllum caffrum*, *Lantana camara*, *Moringa oleifera*, *Tagetes minuta* and *Vangueria infausta* were identified as the most screened plants, showing promising antifungal activity against the highest number of phytopathogens (at least 3 studies reporting =2 pathogens). Among the tested phytopathogens, the genus *Fusarium* (69%) was the most tested fungal strain. Overall, South Africa has limited ethnobotanical studies targeting botanicals with potential to manage microbial-related plant diseases. In addition, more effort should be directed on antimicrobial activity studies relating to the other phytopathogens such as bacteria and viruses as they are cause substantial crop loses.

1. Introduction

Food security is important in the well-being of any country. Globally, it is well recognized that factors such as abiotic and biotic stresses pose major threats to food security. Pathogens (e.g. fungi and nematodes), and pests (approximately 600 insect species) are well-known to be responsible for biotic stress in agriculture (Klassen and Schwartz, 1985; Ul Haq et al., 2020). Particularly, pathogens and pests remain one of the main cause of food insecurity globally. For instance, the potential food losses (total yield losses) due to pests and pathogens are estimated at

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https://doi.org/10.1016/j.cropro.2023.106423
Received 13 April 2023; Received in revised form 12 July 2023; Accepted 11 September 2023
Available online 13 September 2023

36.5% and 38.2% in potatoes and rice, respectively (Oerke, 2019). Furthermore, fungal pathogens cause most of plant diseases (Agrios, 2009), being responsible for an estimated 80% food losses (El Hussein et al., 2014). Fungal infections can destroy a third of all food crops annually (Fisher et al., 2012). The occurrence of plant disease epidemics could easily result in disastrous effects on human community. Historically, a few examples recorded are the Irish Famine caused by potato late blight in the 1840s and the Bengal famine caused by rice brown spot in 1943 (Bourke, 1964; Padmanabhan, 1973; Strange and Scott, 2005).

Generally, synthetic treatments such as pesticides and fungicides are used to manage biotic stress caused by pest and pathogens, respectively (Panth et al., 2020; Ul Haq et al., 2020). To certain degree, there is no doubt these conventional treatments/chemicals have assisted in managing plant diseases. However, their repeated use has been associated with health hazards and negative environmental impacts, as well as emergence of fungicide or pesticide-resistant strains (Abdolmaleki et al., 2008; Abere et al., 2007; Aktar et al., 2009). This has prompted the need to explore alternative economical, eco-friendly and sustainable solutions.

Globally, plants (botanicals) have been widely used for the management of various diseases due to their ability to exert healing effects (Sofowora et al., 2013). A high degree of dependence on plants for health care needs is evident in many developing countries especially for inhabitants in the rural areas. This is often due to the high cost of conventional medicine and readily availability of these medicinal plants. In South Africa, plants are often used to treat different conditions in both humans (Mabona and Van Vuuren, 2013; Mwinga et al., 2019) and domesticated animals (Masika and Afolayan, 2002; McGaw et al., 2020). The presence of therapeutic phytochemicals in plants make them relevant in managing disease causing organisms (Gurjar et al., 2012). If carefully explored, botanicals may serve as an accessible and affordable means of managing plant diseases especially for small-scale and subsistence farmers thereby contributing to the fight against food insecurity.

Given the rich biodiversity in South Africa, it is pertinent to explore how the use of botanicals could be incorporated in the sustainable management of plant diseases caused by pathogenic microbes. Thus, this review entails a critical appraisal of the ethnobotany and antimicrobial effect of botanicals with the potential for managing plant diseases in South Africa.

2. Material and methods

A web-based systematic literature search was conducted from June to October 2022 to identify information on the ethnobotany and antimicrobial activity of plants used in South Africa to manage microbial-related diseases in crops. The systematic review was conducted according to the PRISMA guidelines for reporting systematic reviews and meta-analysis (Moher et al., 2009). Electronic databases such as Google Scholar, JSTOR, ScienceDirect and Scopus were searched for literature, including journal articles, books, theses and dissertations. The databases were searched using keywords/phrases such as South African medicinal plants, botanicals, antifungal, antibacterial, antiviral, antimicrobial effects of medicinal plants, ethnobotany of South Africa, indigenous plant use, medicinal plant use, plant diseases, phytopathogens. In addition, literature was retrieved from the library of the North-West University (NWU), South Africa. To avoid erroneous and ambiguous use of botanical nomenclature (Rivera et al., 2014), verification of the scientific and family names was done using the 'World Flora Online' (Worldflorao nline.org).

The screening of all search results involved reviewing the title and abstract of articles and identifying and selecting eligible publications, downloading the identified research articles, and critically assessing the articles on how they met the inclusion criteria. For a research article to be included in this review, it must have been a published ethnobotanical survey reporting potential antimicrobial effects of botanicals against plant diseases in South Africa. It must also indicate the traditional uses and/or in-vitro and/or in-vivo antimicrobial effects of botanicals against phytopathogens in South Africa. Research articles were excluded from the review if they focused on natural resources (other than plants) or not written in English. In addition, ethnobotanical surveys and antimicrobial activity assays not focusing on South Africa, phytochemistry and toxicity studies were excluded.

3. Results and discussion

3.1. Overview of eligible literature

A total of 1523 studies were recorded from the different scientific databases (Fig. 1), which included journals, theses, dissertations and books. After screening, 1507 studies were excluded based on the inclusion and exclusion criteria while 16 studies were eligible (Fig. 1). In this review, the eligible studies covered most of the provinces in South Africa except Free State and Northern Cape (Table 1). The covered provinces account for 77.78% of the 9 provinces in South Africa. KwaZulu-Natal Province is considered as one of the most research active in South Africa as it is home to the Zulus who extensively use traditional medicine (Viljoen et al., 2019) but most studies recorded in this review were conducted in Gauteng (25%) and Limpopo (25%). Limpopo Province is rich in plant diversity and in the utilisation of traditional medicine (Mongalo and Makhafola, 2018).

In about 37% of the screened studies, the details on the voucher specimens of the evaluated plants were not indicated (Daniel et al., 2015; Mahlo et al., 2010, 2016; Mahlo and Eloff, 2014; Maninjwa, 2020; Mnacube, 2021). Vouchers are important in validating the taxonomy of the plant as well as identifying localities of the taxon. They also form a valuable reference material that can be used for additional research in the future (Culley, 2013; Weckerle et al., 2018).

Ethnobotanical studies documenting the traditional use of medicinal plants in managing microbial-related plant diseases in South Africa remain limited. This ethnobotanical information is often acquired from smallholder and subsistence farmers as well as indigenous knowledge holders in the communities. In South Africa, most ethnobotanical studies are documenting the use of botanicals in managing conditions caused by insects (Odeyemi et al., 2006), pests (Skenjana and Poswal, 2018) and nematodes (Makhubu et al., 2021). Among the 16 eligible studies, the selection criteria of the evaluated plants were based on varying criteria. These include exploring existing literature on the antimicrobial activity of the plants against animal and/or human fungal pathogens, indigenous knowledge-based evidence and the ease of availability of the plants (Table 1). However, some studies did not provide the selection criteria for the evaluated plants (Daniel et al., 2015; Hlokwe et al., 2018, 2020; Mahlo and Eloff, 2014; Mongalo et al., 2018). Most of the screened studies reported that the selection criteria of the evaluated plants were based on previously reported antimicrobial activity of the plants against animal and/or human fungal pathogens (50%). These plants had demonstrated good antifungal effect against human pathogens (Hadian et al., 2011; Pizana et al., 2010).

3.2. Inventory of plants used for managing microbial-related diseases in crops

A total of 66 plant species belonging to 44 families were documented for their antimicrobial activity against pathogens affecting plants. Fabaceae, Solanaceae, Asteraceae and Combretaceae were the most represented families. Fabaceae and Solanaceae were each represented by five plant species while Asteraceae and Combretaceae were each represented by four plant species (Fig. 2). It is unclear whether the representation of the families would be different if the criteria for selection of these plants were based on ethnobotanical studies rather than previous studies exploring the antifungal activity of the plants against human or animal pathogens (Table 1). Asteraceae, Fabaceae and

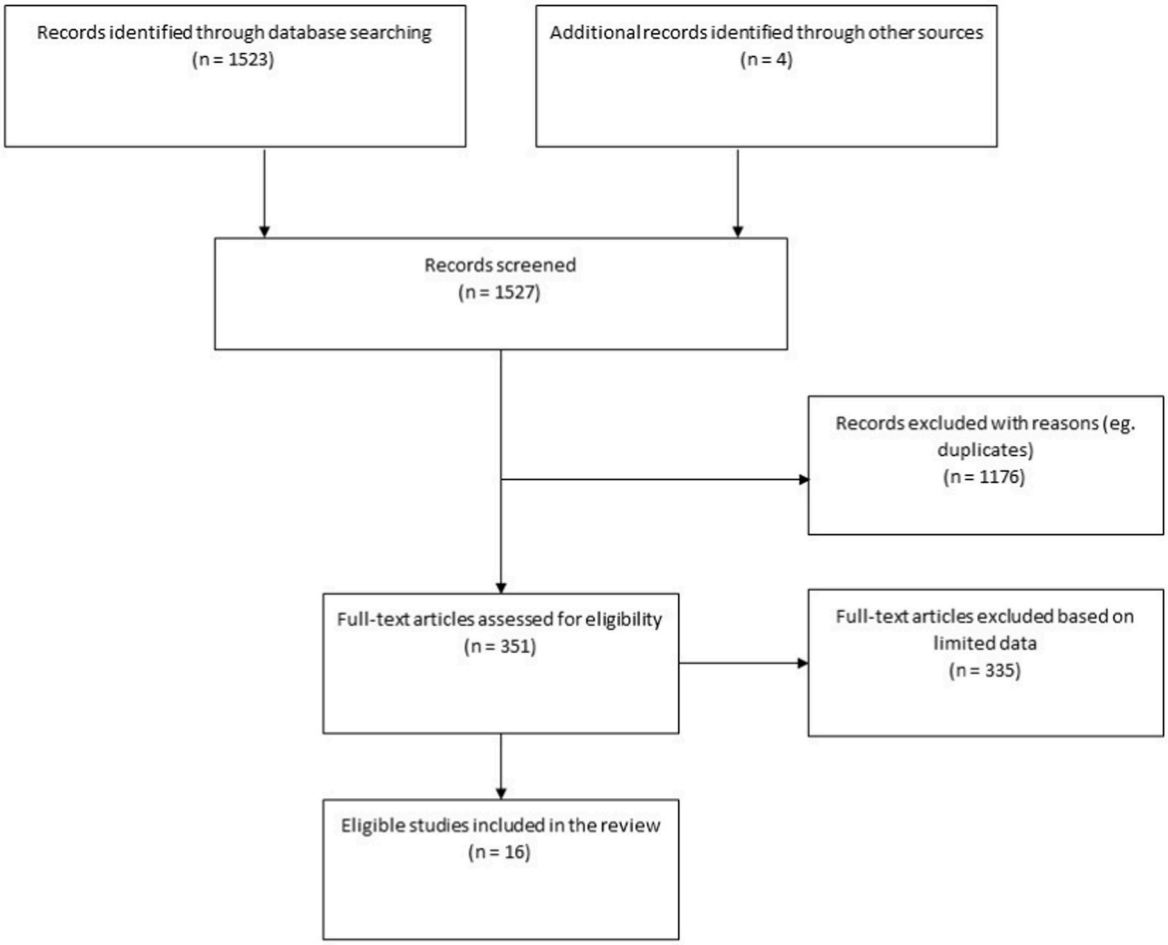

Fig. 1. Flow diagram for the systematic selection of articles included in this review.

Solanaceae were among the top-cited plant families of the world and that are highly commercialized due to their medicinal value (Van Wyk and Wink, 2017). The dominance of Fabaceae and Asteraceae remain evident in African Traditional Medicine (ATM), and they have the most representation of plant species with medicinal value in sub-Saharan Africa (Van Wyk, 2020). In Southern Africa, Asteraceae is one of the mostly used plant family after the Fabaceae (Moteetee and Van Wyk, 2011). The Asteraceae family comprises of a group of plants that have allelopathic properties and are viewed as natural alternatives for protecting crops against pests and pathogens (Araújo et al., 2021). The high utilisation of plant species belonging to Fabaceae and Asteraceae in ATM are well pronounced for the management of various diseases in plants. For instance, an ethnobotanical survey revealed that Asteraceae was the most cited family used to control pests in cabbage in the East Cape Province, South Africa (Skenjana and Poswal, 2018). Based on the ethnobotanical survey by Ali et al. (2022), Fabaceae was the most-cited family used as biopesticides by indigenous people of Plateau State, Nigeria. Likewise, Fabaceae was documented as the most-cited family with pesticidal activity among the Agro-pastoral communities in Mbulu District, Tanzania (Qwarse et al., 2018).

3.3. Antimicrobial screening of plants used for managing microbial-related diseases in crops

This review targeted on all type of antimicrobial (e.g., antibacterial, antifungal and antiviral) assays against phytopathogens. However, all the antimicrobial activity experiments reported on the plants focused on antifungal assay (Table 2). The plants were tested against *Alternaria* spp., *Aspergillus* spp., *Botrytis* spp., *Colletotricum* spp., *Fusarium* spp., *Penicillium* spp., *Pythium* spp., *Phytophthora* spp., *Rhizoctonia* spp., *Trichoderma* spp., and *Xanthomonas* spp. Most of the investigated pathogens are soil-borne phytopathogens (*Aspergillus* spp., *Fusarium* spp., *Penicillium* spp., *Pythium* spp., *Phytophthora* spp., *Rhizoctonia* spp., *Trichoderma* spp.). Soil-borne diseases have been considered a major factor limiting the production of various crops. Soil-borne phytopathogens including *Fusarium* spp., *Phytophthora* spp., *Pythium* spp., *Rhizoctonia* spp., *Sclerotinia* spp. and *Verticillium* spp. are capable of causing 50–75% yield losses in crops such as cotton, maize, wheat and vegetables (Baysal-Gurel and Kabir, 2018; Lewis and Papavizas, 1991; Mihajlovic et al., 2017). In the United States, soil-borne phytopathogens are responsible for about 90% of the 2000 major diseases of the economic crops (Lewis and Papavizas, 1991; Mokhtar and El-Mougy, 2014). Pathogens belonging to genera *Fusarium* (69%), *Aspergillus* (44%) and *Penicillium* (38%) were the most investigated fungal strains as established from the 16 eligible studies (Table 3). Species belonging to genus *Fusarium* are considered to be among the most common fungal pathogens affecting plants (Stefanczyk and Sobkowiak, 2017). *Fusarium* spp. are known to cause various plant diseases. For example, dry rot of potatoes is caused by *F. oxysporum*, *F. roseum* var. *sambucinum* and *F. solani* var. *coeruleum*. *Fusarium solani* is among the common pathogens causing several diseases in many crops. This genus is responsible for dry rot of *Solanum tuberosum*, root and fruit rot of *Cucurbita* spp., sudden death syndrome of *Glycine max*, foot rot of *Phaseolus vulgaris* and, root and stem rot of *Pisum sativum* (McLeod et al., 2001). Globally, fungal pathogens are responsible for most crop losses (Fisher et al., 2012). Hence, the use and popularity of synthetic chemicals such as benomyl, captafol,

Table 1
Overview of reviewed literature documenting the use of botanicals for managing microbial-related conditions in plants.

Reference	Province	Evaluation method	Selection criteria for plants	No. of plants	No. of families	Indication of voucher specimen deposited?
Afolayan et al. (2002)	Eastern Cape	Disc diffusion method	Literature surveys and traditional uses	12	11	Yes
Daniel et al. (2015)	Western Cape	Poisoned food technique (Shahi et al., 2003)	Not specified	1	1	Not specified
Dikhoba et al. (2019)	Mpumalanga	Microplate dilution method (Eloff, 1998a)	Availability in the National Botanical Garden	25	22	Yes
Eloff et al. (2017)	Gauteng	Microplate dilution method (Eloff, 1998a)	Traditional uses	1	1	Yes
Hlokwe et al. (2020)	Limpopo	Not specified	Not specified	2	2	Yes
Hlokwe et al. (2018)	Limpopo	Not specified	Not specified	2	2	Yes
Mahlo and Eloff (2014)	Mpumalanga	Microplate dilution method (Eloff, 1998a)	Not specified	1	1	Not specified
Mahlo et al. (2010)	Mpumalanga	Microplate dilution method (Eloff, 1998a)	Good antimicrobial activity of leaf extracts against two human and animal fungal pathogens	6	5	Not specified
Mahlo et al. (2016)	Mpumalanga	Microplate dilution method (Eloff, 1998a)	Excellent antimicrobial activity observed against two animal fungal pathogens (*Candida albicans* and *Cryptococcus neoformans*)	6	5	Not specified
Mandiriza et al. (2018)	Gauteng and Limpopo	Microplate dilution method (Eloff, 1998a)	Literature on antimicrobial activity against plant pathogens	6	6	Yes
Maninjwa (2020)	Western Cape	Microplate dilution method (Eloff, 1998a)	Literature surveys on antifungal activity	1	1	Not specified
Mnacube (2021)	KwaZulu-Natal	Disc diffusion method	Literature surveys on antifungal activity	1	1	Not specified
Mongalo et al. (2018)	KwaZulu-Natal	Microplate dilution method (Eloff, 1998a)	Not specified	10	8	Yes
Seepe et al. (2020a)	Gauteng and Limpopo	Microplate dilution method (Eloff, 1998a)	Literature on antimicrobial activity against animal and/or human fungal pathogens	13	9	Yes
Seepe et al. (2020b)	Gauteng and Limpopo	Not specified	In-vivo antifungal activities against different *Fusarium* species	8	5	Yes
Thembo et al. (2010)	Gauteng and North West	Microplate dilution method (Eloff, 1998a)	Traditional uses	4	4	Yes

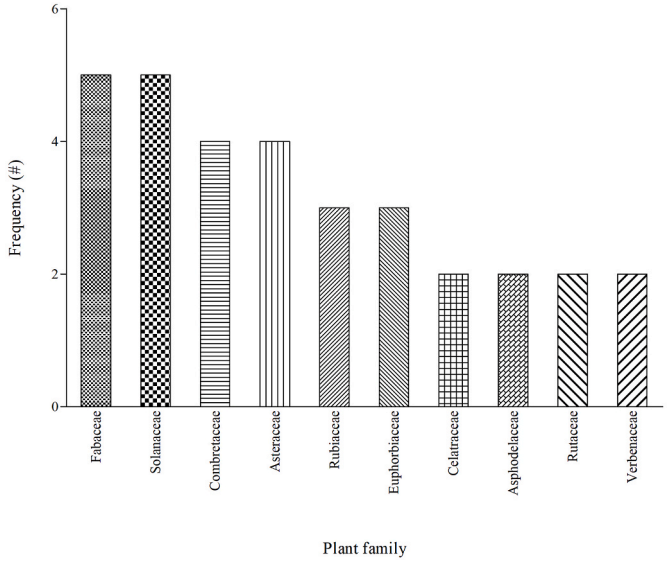

Fig. 2. A representation of major (with =2 mentions) plant families used for managing microbial-related crop diseases in South Africa. The remaining 35 plant families were each mentioned once and are fully listed in Table 2.

carboxanilides, mancozeb, morpholines, thiabendazole (Russell, 2005), fosetyl-Al, carbamate and benzimidazole (Klittich, 2008), which are examples of fungicides used to control diseases of vegetables, cereals and fruits.

In this review, most of the experiments entailed in-vitro assays, only 3 out of 16 studies utilised in-vivo assays. In-vivo assays provide a more accurate biological activity of plants. However, their limited use is often attributed to economic and ethical concerns. In-vivo assays are important, and there is no guarantee an in-vitro activity will produce an in-vivo effect (Houghton et al., 2007). In-vitro antifungal screening of *Melia azedarach* and *Combretum erythrophyllum* leaf extracts indicated a significant effect against *F. verticillioides* (0.04 mg/ml), *F. proliferatum* (0.04 mg/ml), *F. solani* (0.04 mg/ml) and *F. graminearum* (0.08 mg/ml) (Seepe et al., 2020a). However, the subsequent in-vivo evaluation demonstrated good antifungal activity against only *F. proliferatum* (Seepe et al., 2020b). This observed difference in the in-vivo assay could be due to the dose range of the extracts, if they were of potential therapeutic relevance. A dose range of 100–200 mg/kg for in-vivo studies of extracts and of 100–200 μg/ml should be assumed as being the upper limit for meaningful pharmacological studies (Heinrich et al., 2020).

Antimicrobial studies on the plant extracts were conducted using a wide range of assays (Fig. 3). The most commonly used antimicrobial assay was the microplate dilution (62.5%) assay, which is a popular and robust method that was developed by Eloff (1998a). This method determines the minimum inhibitory concentration (MIC) of the extract and involves the use of *p*-iodonitrotetrazolium salt (INT) as the cellular growth indicator. Generally, MIC is recognized as a better way to express the antimicrobial activity of an extract or compound as it represents the lowest concentration of a substance that inhibits the growth of a pathogen (Eloff, 2019). From the screened studies, noteworthy antimicrobial activity was considered at MIC value of =0.1 mg/ml (Gibbons, 2004; Rios and Recio, 2005). Microplate dilution method is by no means a perfect method, however, it is the widely accepted and preferred method (Othman et al., 2011; Van Vuuren and Holl, 2017). Disc diffusion method (13%) was indicated in a few of the 16 eligible studies. This method is deemed not appropriate due to the lack of diffusion of non-polar compounds and difficulty of obtaining reproducible results among different laboratories (Eloff, 2019).

Table 2
Examples of medicinal plants with antimicrobial activity against phytopathogens. Verification of the species and family names was done using 'World Flora Online'(Worldfloraonline.org.).

No.	Plant species, Family	Test system	Plant part used, solvent (s)	Pathogen(s)/disease(s) managed	Key findings	Positive control	Reference
1.	*Acokanthera oppositifolia* (Lam.) Codd. Apocynaceae	*In-vitro*	Leaves Acetone	*Aspergillus flavus*, *Aspergillus ochraceous* and *Fusarium verticilloides*	No significant activity	Amphotericin B – *A. flavus*, *A. ochraceous* – 0.16 mg/ml *F. verticilloides* – 1.56 mg/ml	Dikhoba et al. (2019)
2.	*Agapanthus caulescens* Spreng Amaryllidaceae	*In-vitro*	Leaves Acetone and water	*Xanthomonas campestris* pv. *campestris* causing black rot in rapes	Acetone extract was moderately active, 0.39 mg/ml	Neomycin (0.2 mg/ml)	Mandiriza et al. (2018)
3.	*Allium sativum* L. Amaryllidaceae	*In-vitro*	Cloves Water and ethanol	*Botrytis cinerea*, *Penicillium expansum* and *Neofabraea alba*	Complete inhibition (100%) of *B. cinerea* at 60% and 80% concentrations	Not specified	Daniel et al. (2015)
4.	*Aloe ferox* Mill. Asphodelaceae	*In-vitro*	Leaves Acetone	*Alternaria alternaria* and *Aspergillus niger*	Insignificant growth inhibition	2% Acetone	Afolayan et al. (2002)
5.	*Amaranthus spinosus* L. Amaranthaceae	*In-vitro*	Leaves Hexane, dichloromethane and methanol	*Fusarium verticillioides*, *F. proliferatum*	Good antifungal activity with hexane, methanol extracts	Amphotericin B, Cantus – 0.04 mg/ml	Thembo et al. (2010)
6.	*Apodytes dimidiata* E.Mey ex Arn. Metteniusaceae	*In-vitro*	Leaves Acetone	*Aspergillus flavus*, *Aspergillus ochraceous* and *Fusarium verticilloides*	No significant activity	Amphotericin B – *A. flavus*, *A. ochraceous* – 0.16 mg/ml *F. verticilloides* – 1.56 mg/ml	Dikhoba et al. (2019)
7.	*Arctotis arctotoides* L.F. O. Hoffm. Asteraceae	*In-vitro*	Shoot Acetone	*Alternaria alternaria* and *Aspergillus niger*	100% growth inhibition	2% Acetone	Afolayan et al. (2002)
8.	*Artemesia afra* Jacq. ex Willd. Asteraceae	*In-vitro*	Leaves Acetone	*Aspergillus flavus*, *Aspergillus ochraceous* and *Fusarium verticilloides*	No significant activity	Amphotericin B – *A. flavus*, *A. ochraceous* – 0.16 mg/ml *F. verticilloides* – 1.56 mg/ml	Dikhoba et al. (2019)
9.	*Bauhinia galpini* N.E.Br. Fabaceae	*In-vitro*	Leaves Acetone	*Aspergillus flavus*, *Aspergillus ochraceous* and *Fusarium verticilloides*	No significant activity	Amphotericin B – *A. flavus*, *A. ochraceous* – 0.16 mg/ml F. *verticilloides* – 1.56 mg/ml	Dikhoba et al. (2019)
		In-vitro	Leaves Water: methanol (1:1), dichloromethane	*Fusarium graminearum*, *F. verticillioides*, *F. oxysporum*, *Aspergillus parasiticus*, *A. ochraceous*, *A. flavus*	Good antifungal activity against *Aspergillus parasiticus*, *A. flavus* with organic solvent	Amphotericin B – *Fusarium graminearum*, *F. oxysporum* – 0.04 gm/ml, *F. verticillioides* - 0.06 mg/ml, *Aspergillus parasiticus*, *A. flavus* – 0.02 mg/ml, *A. ochraceous* – 0.03 mg/ml	Mongalo et al. (2018)
10.	*Brachylaena discolor* DC. Asteraceae	*In-vitro*	Leaves Acetone	*Aspergillus flavus*, *Aspergillus ochraceous* and *Fusarium verticilloides*	No significant activity	Amphotericin B – *A. flavus*, *A. ochraceous* – 0.16 mg/ml *F. verticilloides* – 1.56 mg/ml	Dikhoba et al. (2019)
11.	*Breonadia salicina* (Vahl) Hepper and J.R.I Wood Rubiaceae	*In-vitro*	Leaves Acetone, hexane, dichloromethane and methanol	*Aspergillus niger*, *Aspergillus parasiticus*, *Colletotricum gloeosporioides*, *Penicillium janthinellum*, *P. expansum*, *Trichoderma harzianum* and *F. oxysporum*	Good antifungal activity against *F. oxysporum* with hexane extracts	Amphotericin B – For *A. parasiticus* and *A. niger* was 0.02 mg/ml after 24 h and 48 h incubation and for the other fungi was <0.02 mg/ml.	Mahlo et al. (2010)
		In-vitro	Leaves Acetone	*P. expansum*, *P. janthinellum* and *P. digitatum*	Good antifungal activity against *P. janthinellum* – 0.08 mg/ml	Amphotericin B *P. expansum*, *P. janthinellum* – 0.003 mg/ml *P. digitatum* – 0.08 mg/ml.	Mahlo and Eloff (2014)
		In-vitro	Leaves Acetone, hexane, dichloromethane and methanol	*Aspergillus niger*, *Aspergillus parasiticus*, *Colletotricum gloeosporioides*, *Penicillium janthinellum*, *P. expansum*, *Trichoderma harzianum* and *F. oxysporum*	Good antifungal activity against *F. oxysporum* with hexane extracts	Amphotericin B – *A. parasiticus* and *A. niger* - 0.02 mg/ml. Other fungi <0.02 mg/ml.	Mahlo et al. (2016)
		In-vitro	Leaves Acetone	*Aspergillus flavus*, *Aspergillus ochraceous* and *Fusarium verticilloides*	No significant activity	Amphotericin B – *A. flavus*, *A. ochraceous* – 0.16 mg/ml F. *verticilloides* – 1.56 mg/ml	Dikhoba et al. (2019)

(*continued on next page*)

Table 2 (*continued*)

No.	Plant species, Family	Test system	Plant part used, solvent (s)	Pathogen(s)/disease(s) managed	Key findings	Positive control	Reference
12.	*Bucida buceras* L. Combretaceae	*In-vitro*	Leaves Acetone, hexane, dichloromethane and methanol	*Aspergillus niger*, *Aspergillus parasiticus*, *Colletotricum gloeosporioides*, *Penicillium janthinellum*, *P. expansum*, *Trichoderma harzianum* and *F. oxysporum*	Good antifungal activity against *Penicillium janthinellum*, *P. expansum*, *Trichoderma harzianum* and *F. oxysporum* with acetone extracts. Good antifungal activity against *Penicillium janthinellum*, *Trichoderma harzianum* and *F. oxysporum* with methanol extracts. Good antifungal activity against *Penicillium janthinellum* and *Trichoderma harzianum* with hexane extracts.	Amphotericin B – For *A. parasiticus* and *A. niger* was 0.02 mg/ml after 24 h and 48 h incubation and for the other fungi was <0.02 mg/ml.	Mahlo et al. (2010)
		In-vitro	Leaves Acetone, hexane, dichloromethane and methanol	*Aspergillus niger*, *Aspergillus parasiticus*, *Colletotricum gloeosporioides*, *Penicillium janthinellum*, *P. expansum*, *Trichoderma harzianum* and *F. oxysporum*	Good antifungal activity against *Penicillium janthinellum*, *P. expansum*, *Trichoderma harzianum* and *F. oxysporum* with acetone extracts. Good antifungal activity against *Penicillium janthinellum*, *Trichoderma harzianum* and *F. oxysporum* with methanol extracts. Good antifungal activity against *Penicillium janthinellum* and *Trichoderma harzianum* with hexane extracts.	Amphotericin B – *A. parasiticus* and *A. niger* - 0.02 mg/ml. Other fungi <0.02 mg/ml.	Mahlo et al. (2016)
13.	*Bulbine frutescens* Willd. Asphodelaceae	*In-vitro*	Whole plant Acetone	*Fusarium oxysporum*	Good antifungal activity observed	Mancozeb – 1.50 mg/ml	Maninjwa (2020)
14.	*Capparis tamentosa* Lam. Capparaceae	*In-vitro*	Leaves Acetone	*Aspergillus flavus*, *Aspergillus ochraceous* and *Fusarium verticilloides*	No significant activity	Amphotericin B – *A. flavus*, *A. ochraceous* – 0.16 mg/ml *F. verticilloides* – 1.56 mg/ml	Dikhoba et al. (2019)
15.	*Carpobrotus eludis* L. Mesembryanthemaceae	*In-vitro*	Leaves Water and methanol (1:1), dichloromethane	*Fusarium graminearum*, *F. verticillioides*, *F. oxysporum*, *Aspergillus parasiticus*, *A. ochraceous*, *A. flavus*	Good antifungal activity against *Aspergillus parasiticus*, *A. flavus* with organic solvent.	Amphotericin B – *Fusarium graminearum*, *F. oxysporum* – 0.04 mg/ml, *F. verticillioides* - 0.06 mg/ml, *Aspergillus parasiticus*, *A. flavus* – 0.02 mg/ml, *A. ochraceous* – 0.03 mg/ml	Mongalo et al. (2018)
16.	*Cheilanthes viridis* Forsk. Adiantaceae	*In-vitro*	Fronds Acetone	*Alternaria alternaria* and *Aspergillus niger*	Insignificant growth inhibition	2% Acetone	Afolayan et al. (2002)
17.	*Chlorophytum comosum* (Thunb) Jacq Anthericaceae	*In-vitro*	Whole plant Acetone and water	*Xanthomonas campestris* pv. *campestris* causing black rot in rapes	No significant activity	Neomycin (0.2 mg/ml)	Mandiriza et al. (2018)
18.	*Combretum caffrum* Kuntze Combretaceaea	*In-vitro*	Bark and leaves Acetone	*Alternaria alternaria* and *Aspergillus niger*	100% growth Inhibition on *Aspergillus niger*	2% Acetone	Afolayan et al. (2002)
		In-vitro	Leaves Acetone	*Aspergillus flavus*, *Aspergillus ochraceous* and *Fusarium verticilloides*	No significant activity	Amphotericin B – *A. flavus*, *A. ochraceous* – 0.16 mg/ml F. *verticilloides* – 1.56 mg/ml	Dikhoba et al. (2019)
19.	*Combretum erythrophyllum* Sond. Combretaceae	*In-vitro*	Leaves Water, ethyl acetate and acetone	*F. verticillioides*, *F. proliferatum, F. solani* and *F. graminearum Fusarium verticillioides*, *F. proliferatum*,	Ethyl acetate extract (mg/ml): *F. verticillioides* (0.04), *F. proliferatum* (0.04), *F. solani* (0.08) Acetone extract (mg/ml): *F. verticillioides* (0.04), *F. proliferatum* (0.04), *F. solani* (0.04), *F. graminearum* (0.08)	Amphotericin B (μg/ml): *F. verticillioides* (2.93)	Seepe et al. (2020a)
		In-vivo	Leaves Ethyl acetate and acetone	*F. solani*, *F. graminearum*, *F. equiseti*, *F. semitectum*, *F. subglutinans, F. chlamydosporum*	More than 50% inhibition against *F. proliferatum* with ethyl acetate extracts	*F. proliferatum* (0.37) *F. solani* (0.37) *F. graminearum* (187.50) Amphotericin B at 2.5 mg/ml	Seepe et al. (2020b)

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Table 2 (*continued*)

No.	Plant species, Family	Test system	Plant part used, solvent (s)	Pathogen(s)/disease(s) managed	Key findings	Positive control	Reference
20.	*Combretum molle* R.Br. ex G.Don. Combretaceae	*In-vitro*	Leaves Water, ethyl acetate and acetone	*F. verticillioides*, *F. proliferatum*, *F. solani* and *F. graminearum*	Water extract (mg/ml): *F. proliferatum* (0.04), *F. solani* (0.04) Ethyl acetate extract (mg/ml): *F. proliferatum* (0.04), *F. solani* (0.04) Acetone extract (mg/ml): *F. proliferatum* (0.04), *F. solani* (0.04)	Amphotericin B (μg/ml): *F. verticillioides* (2.93) *F. proliferatum* (0.37) *F. solani* (0.37) *F. graminearum* (187.50)	Seepe et al. (2020a)
		In-vivo	Leaves Ethyl acetate and acetone	*Fusarium verticillioides*, *F. proliferatum*, *F. solani*, *F. graminearum*, *F. equiseti*, *F. semitectum*, *F. subglutinans*, *F. chlamydosporum*	Not specified	Amphotericin B at 2.5 mg/ml	Seepe et al. (2020b)
21.	*Curtisia dentate* (Burm.f.) C.A.Sm. Cornaceae	*In-vitro*	Leaves Acetone	*Aspergillus flavus*, *Aspergillus ochraceous* and *Fusarium verticilloides*	Good antifungal activity against *Aspergillus ochraceous*	Amphotericin B – *A. flavus*, *A. ochraceous* – 0.16 mg/ml *F. verticilloides* – 1.56 mg/ml	Dikhoba et al. (2019)
22.	*Cymbopogon citratus* Stapf Poaceae	*In-vitro*	Leaves and stem Acetone and water	*Xanthomonas campestris* pv. *campestris* causing black rot in rapes	Acetone extract of *Cymbopogon citratus* had a notable antimicrobial activity MIC value less than 0.1 mg/ml. Water extract was moderately active, 0.39 mg/ml.	Neomycin (0.2 mg/ml)	Mandiriza et al. (2018)
23.	*Dracaena mannii* Bakker Asparagaceae	*In-vitro*	Leaves Acetone	*Aspergillus flavus*, *Aspergillus ochraceous* and *Fusarium verticilloides*	No significant activity	Amphotericin B – *A. flavus*, *A. ochraceous* – 0.16 mg/ml *F. verticilloides* – 1.56 mg/ml	Dikhoba et al. (2019)
24.	*Ficus natelensis* Hochst. Moraceae	*In-vitro*	Leaves Acetone	*Aspergillus flavus*, *Aspergillus ochraceous* and *Fusarium verticilloides*	No significant activity	Amphotericin B – *A. flavus*, *A. ochraceous* – 0.16 mg/ml *F. verticilloides* – 1.56 mg/ml	Dikhoba et al. (2019)
25.	*Grewia occidentalis* L. Tiliaceae	*In-vitro*	Twig and leaves Acetone	*Alternaria alternaria* and *Aspergillus niger*	100% growth Inhibition on *Alternaria alternaria*	2% Acetone	Afolayan et al. (2002)
26.	*Harpephyllum caffrum* Bernh. ex Krauss Anacardiaceae	*In-vitro*	Leaves Water, ethyl acetate and acetone	*F. verticillioides*, *F. proliferatum*, *F. solani* and *F. graminearum*	Ethyl acetate extract (mg/ml): *F. verticillioides* (0.08), *F. proliferatum* (0.04), *F. solani* (0.08) Acetone extract (mg/ml): *F. verticillioides* (0.08), *F. proliferatum* (0.04), *F. solani* (0.04), *F. graminearum* (0.08)	Amphotericin B (μg/ml): *F. verticillioides* (2.93) *F. proliferatum* (0.37) *F. solani* (0.37) *F. graminearum* (187.50)	Seepe et al. (2020a)
		In-vitro	Leaves Acetone, hexane, dichloromethane and methanol	*Aspergillus niger*, *Aspergillus parasiticus*, *Colletotricum gloeosporioides*, *Penicillium janthinellum*, *P. expansum*, *Trichoderma harzianum* and *F. oxysporum*	Good antifungal activity against *Trichoderma harzianum* and *Penicillium janthinellum* with acetone and methanol extracts	Amphotericin B – For *A. parasiticus* and *A. niger* was 0.02 mg/ml after 24 h and 48 h incubation and for the other fungi was <0.02 mg/ml.	Mahlo et al. (2010)
		In-vitro	Leaves Acetone, hexane, dichloromethane and methanol	*Aspergillus niger*, *Aspergillus parasiticus*, *Colletotricum gloeosporioides*, *Penicillium janthinellum*, *P. expansum*, *Trichoderma harzianum* and *F. oxysporum*	Good antifungal activity against *Trichoderma harzianum* and *Penicillium janthinellum* with acetone and methanol extracts	Amphotericin B – *A. parasiticus* and *A. niger* - 0.02 mg/ml. Other fungi <0.02 mg/ml.	Mahlo et al. (2016)
		In-vitro	Leaves Acetone	*Aspergillus flavus*, *Aspergillus ochraceous* and *Fusarium verticilloides*	No significant activity	Amphotericin B – *A. flavus*, *A. ochraceous* – 0.16 mg/ml F. *verticilloides* – 1.56 mg/ml	Dikhoba et al. (2019)
		In-vitro	Leaves Water: methanol (1:1), dichloromethane	*Fusarium graminearum*, *F. verticillioides*, *F. oxysporum*, *Aspergillus parasiticus*, *A. ochraceous*, *A. flavus*	Good antifungal activity against *Aspergillus parasiticus*, *A. ochraceous* with organic solvent	Amphotericin B – *Fusarium graminearum*, *F. oxysporum* – 0.04 gm/ml, *F. verticillioides* - 0.06 mg/ml, *Aspergillus parasiticus*, *A. flavus* – 0.02 mg/ml, *A. ochraceous* – 0.03 mg/ml	Mongalo et al. (2018)

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Table 2 (*continued*)

No.	Plant species, Family	Test system	Plant part used, solvent (s)	Pathogen(s)/disease(s) managed	Key findings	Positive control	Reference
27.	*Heteromorpha arborescens* (Spreng.) Charm & Schltdl. Apiaceae	*In-vitro*	Leaves Acetone	*Aspergillus flavus*, *Aspergillus ochraceous* and *Fusarium verticilloides*	No significant activity	Amphotericin B – *A. flavus*, *A. ochraceous* – 0.16 mg/ml *F. verticilloides* – 1.56 mg/ml	Dikhoba et al. (2019)
28.	*Kirkia wilmsii* Engl. Kirkiaceae	*In-vitro*	Leaves Acetone	*Aspergillus flavus*, *Aspergillus ochraceous* and *Fusarium verticilloides*	No significant activity	Amphotericin B – *A. flavus*, *A. ochraceous* – 0.16 mg/ml *F. verticilloides* – 1.56 mg/ml	Dikhoba et al. (2019)
29.	*Lantana camara* L. Verbenaceae	*In-vitro*	Leaves Water, ethyl acetate and acetone	*Fusarium verticillioides*, *F. proliferatum*, *F. solani* and *F. graminearum*	Water extract (mg/ml): *F. verticillioides* (0.04)	Amphotericin B (μg/ml): *F. verticillioides* (2.93) *F. proliferatum* (0.37) *F. solani* (0.37) *F. graminearum* (187.50)	Seepe et al. (2020a)
		In-vitro	Leaves and flowers Acetone and water	*Xanthomonas campestris* pv. *campestris* causing black rot in rapes	Ethyl acetate extract (mg/ml): *F. proliferatum* (0.04), *F. graminearum* (0.08) Acetone extract (mg/ml): *F. proliferatum* (0.04), *F. solani* (0.04) No notable activity	Neomycin (0.2 mg/ml)	Mandiriza et al. (2018)
		In-vivo	Leaves Ethyl acetate and acetone	*Fusarium verticillioides*, *F. proliferatum*, *F. solani*, *F. graminearum*, *F. equiseti*, *F. semitectum*, *F. subglutinans, F. chlamydosporum*	Not specified	Amphotericin B at 2.5 mg/ml	Seepe et al. (2020b)
30.	*Lavandula angustifolia* Mill Lamiaceae	*In-vitro*	Leaves, flowers and stem Acetone and water	*Xanthomonas campestris* pv. *campestris* causing black rot in rapes	No significant activity	Neomycin (0.2 mg/ml)	Mandiriza et al. (2018)
31.	*Lippia javanica* Spreng. Verbenaceae	*In-vitro*	Leaves Hexane, dichloromethane and methanol	*Fusarium verticillioides*, *F. proliferatum*	Good antifungal activity with hexane, dichloromethane extracts	Amphotericin B, Cantus – 0.04 mg/ml	Thembo et al. (2010)
32.	*Maesa lanceolata* Forsk Myrsinaceae	*In-vitro*	Leaves Water: methanol (1:1), dichloromethane	*Fusarium graminearum*, *F. verticillioides*, *F. oxysporum*, *Aspergillus parasiticus*, *A. ochraceous*, *A. flavus*	Good antifungal activity against *Aspergillus parasiticus* with organic solvent.	Amphotericin B – *Fusarium graminearum*, *F. oxysporum* – 0.04 mg/ml, *F. verticillioides* - 0.06 mg/ml, *Aspergillus parasiticus*, *A. flavus* – 0.02 mg/ml, *A. ochraceous* – 0.03 mg/ml	Mongalo et al. (2018)
33.	*Malva parvifolia* L. Malvaceae	*In-vitro*	Shoot Acetone	*Alternaria alternaria* and *Aspergillus niger*	100% growth Inhibition on *Alternaria alternaria*	2% Acetone	Afolayan et al. (2002)
34.	*Markhamia obtusifolia* (Baker) Sprague Bignoniaceae	*In-vitro*	Leaves Acetone	*Aspergillus flavus*, *Aspergillus ochraceous* and *Fusarium verticilloides*	Good antifungal activity against *Aspergillus flavus* and *Fusarium verticilloides*	Amphotericin B – *A. flavus*, *A. ochraceous* – 0.16 mg/ml *F. verticilloides* – 1.56 mg/ml	Dikhoba et al. (2019)
35.	*Maytenus undata* (Thunb.) Blakelock Celastraceae	*In-vitro*	Leaves Acetone	*Aspergillus flavus*, *Aspergillus ochraceous* and *Fusarium verticilloides*	Good antifungal activity against *Aspergillus ochraceous*	Amphotericin B – *A. flavus*, *A. ochraceous* – 0.16 mg/ml *F. verticilloides* – 1.56 mg/ml	Dikhoba et al. (2019)
36.	*Melia azedarach* L. Meliaceae	*In-vitro*	Leaves Water, ethyl acetate and acetone	*F. verticillioides*, *F. proliferatum*, *F. solani* and *F. graminearum*	Ethyl acetate extract (mg/ml): *F. proliferatum* (0.04), *F. solani* (0.08), *F. graminearum* (0.08) Acetone extract (mg/ml): *F. verticillioides* (0.08), *F. proliferatum* (0.08), *F. solani* (0.04)	Amphotericin B (μg/ml): *F. verticillioides* (2.93) *F. proliferatum* (0.37) *F. solani* (0.37) *F. graminearum* (187.50)	Seepe et al. (2020a)
		In-vivo	Leaves Ethyl acetate and acetone	*Fusarium verticillioides*, *F. proliferatum*, *F. solani*, *F. graminearum*, *F. equiseti*, *F. semitectum*, *F. subglutinans, F. chlamydosporum*	More than 50% inhibition against *F. proliferatum* with ethyl acetate extracts	Amphotericin B at 2.5 mg/ml	Seepe et al. (2020b)
37.	*Melianthus comosus* Vahl Francoaceae	*In-vitro*	Leaves Acetone, methanol, water, hexane, ethyl acetate, dichloromethane, carbon tetrachloride,	*F. oxysporum*, *Penicillium janthinellum*, *Colletotrichum gloeosporioides*, *Penicillium expansum*, *Trichoderma harzianum*, *Rhizoctonia*	Acetone extract (mg/ml): *Rhizoctonia solani* (0.02), *Penicillium janthinellum* (0.04), *Penicillium expansum* (0.04), *Colletotrichum*	Not specified	Eloff et al. (2017)

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Table 2 (*continued*)

No.	Plant species, Family	Test system	Plant part used, solvent (s)	Pathogen(s)/disease(s) managed	Key findings	Positive control	Reference
			diethyl ether, chloroform, ethanol	*solani*, *Pythium ultimum*, *Phytophthora nicotiana*	*gloeosporioide* (0.04), *Phytophthora nicotiana* (0.04) Ethanol extract (mg/ml): *F. oxysporum* (0.04)		
38.	*Millettia grandis* (E.Mey.) Skeels Fabaceae	*In-vitro*	Leaves Acetone	*Aspergillus flavus*, *Aspergillus ochraceous* and *Fusarium verticilloides*	No significant activity	Amphotericin B – *A. flavus, A. ochraceous* – 0.16 mg/ml F. *verticilloides* – 1.56 mg/ml	Dikhoba et al. (2019)
		In-vitro	Leaves Water: methanol (1:1), dichloromethane	*Fusarium graminearum*, *F. verticillioides*, *F. oxysporum, Aspergillus parasiticus*, *A. ochraceous*, *A. flavus*	Good antifungal activity against *Fusarium graminearum*, *F. oxysporum*, *Aspergillus parasiticus*, *A. ochraceous* with organic solvent.	Amphotericin B – *Fusarium graminearum, F. oxysporum* – 0.04 gm/ml, *F. verticillioides* - 0.06 mg/ml, *Aspergillus parasiticus*, *A. flavus* – 0.02 mg/ml, *A. ochraceous* – 0.03 mg/ml	Mongalo et al. (2018)
39.	*Monsonia burkeana* Planch. ex Harv. & Sond. Geraniaceae	*In-vitro*	Whole plant Methanol	*Rhizoctonia solani*	Highest mycelia growth inhibition at a concentration of 8 g/ml	Not specified	Hlokwe et al. (2020)
		In-vitro	Whole plant Methanol	*F. oxysporum f.* sp. *lycopersici*	Highest mycelial growth inhibition was recorded at concentrations 8 g/ml (61%) and 1 g/ml (76%)	Not specified	Hlokwe et al. (2018)
		In-vivo	Whole plant Methanol	*F. oxysporum f.* sp. *lycopersici*	All treatments were effective in inhibiting fungal growth; however, increased concentrations for *Monsonia burkeana* extracts did not influence the intensity of *Fusarium oxysporum f.* sp. *lycopersici*	Not specified	Hlokwe et al. (2018)
40.	*Moringa oleifera* Lam Moringaceae	*In-vitro*	Leaves Methanol	*Rhizoctonia solani*	Highest pathogen growth suppression was obtained at a concentration of 6 g/ml	Not specified	Hlokwe et al. (2020)
		In-vitro	Leaves Methanol	*Fusarium oxysporum f.* sp. *lycopersici*	Highest mycelial growth inhibition was recorded at a concentration of 6 g/ml	Not specified	Hlokwe et al. (2018)
		In-vivo	Leaves Methanol	*Fusarium oxysporum f.* sp. *lycopersici*	All treatments were effective in inhibiting fungal growth; however, increased concentrations for *Moringa oleifera* extracts did not influence the intensity of *Fusarium oxysporum f.* sp. *lycopersici*	Not specified	Hlokwe et al. (2018)
		In-vitro	Leaves Methanol, acetone, ethyl acetate and water	*Fusarium oxysporum*	All treatments were effective in inhibiting fungal growth; however, as the solvent concentration increased from 30 to 70%, inhibition decreased	Not specified	Mnacube (2021)
		In-vivo	Leaves Methanol, acetone, ethyl acetate and water	*Fusarium oxysporum*	All treatments were effective in inhibiting fungal growth. However, increased concentrations for *Moringa oleifera* extracts did not influence the intensity of *Fusarium oxysporum*	Not specified	Mnacube (2021)
41.	*Mystroxylon aethiopicum* (Thunb.) Loes. Celastraceae	*In-vitro*	Leaves Acetone	*Aspergillus flavus*, *Aspergillus ochraceous* and *Fusarium verticilloides*	Good antifungal activity against *Fusarium verticilloides*	Amphotericin B – *A. flavus*, *A. ochraceous* – 0.16 mg/ml *F. verticilloides* – 1.56 mg/ml	Dikhoba et al. (2019)
42.	*Nicotiana glauca* Graham Solanaceae	*In-vitro*	Leaves Water, ethyl acetate and acetone	*F. verticillioides*, *F. proliferatum*, *F. solani* and *F. graminearum*	Ethyl acetate (mg/ml): *F. proliferatum* (0.04), *F. solani* (0.04) Acetone extract (mg/ml): *F. solani* (0.04), *F. graminearum* (0.0)	Amphotericin B (μg/ml): *F. verticillioides* (2.93) *F. proliferatum* (0.37) *F. solani* (0.37) *F. graminearum* (187.50)	Seepe et al. (2020a)
		In-vivo	Leaves Ethyl acetate and acetone	*Fusarium verticillioides*, *F. proliferatum*, *F. solani*, *F. graminearum*, *F. equiseti*, *F. semitectum*,	Not specified	Amphotericin B at 2.5 mg/ml	Seepe et al. (2020b)

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Table 2 (*continued*)

No.	Plant species, Family	Test system	Plant part used, solvent (s)	Pathogen(s)/disease(s) managed	Key findings	Positive control	Reference
				F. subglutinans, F. chlamydosporum.			
43.	*Olea europaea* L. Oleaceae	*In-vitro*	Leaves Water, ethyl acetate and acetone	*F. verticillioides*, *F. proliferatum*, *F. solani* and *F. graminearum*	Water extract (mg/ml): *F. verticillioides* (0.08), *F. proliferatum* (0.04) Ethyl acetate (mg/ml): *F. proliferatum* (0.04), *F. solani* (0.04), *F. graminearum* (0.02) Acetone extract (mg/ml): *F. proliferatum* (0.04), *F. solani* (0.04), *F. graminearum* (0.02)	Amphotericin B (μg/ml): *F. verticillioides* (2.93) *F. proliferatum* (0.37) *F. solani* (0.37) *F. graminearum* (187.50)	Seepe et al. (2020a)
44.	*Olinia ventosa* Cufod Penaeaceae	*In-vitro*	Leaves Acetone, hexane, dichloromethane and methanol	*Aspergillus niger*, *Aspergillus parasiticus*, *Colletotricum gloeosporioides*, *Penicillium janthinellum*, *P. expansum*, *Trichoderma harzianum* and *F. oxysporum*	Good antifungal activity against *Trichoderma harzianum* for all extracts and good antifungal activity against *Penicillium janthinellum* with acetone extracts	Amphotericin B – For *A. parasiticus* and *A. niger* was 0.02 mg/ml after 24 h and 48 h incubation and for the other fungi was <0.02 mg/ml.	Mahlo et al. (2010)
		In-vitro	Leaves Acetone, hexane, dichloromethane and methanol	*Aspergillus niger*, *Aspergillus parasiticus*, *Colletotricum gloeosporioides*, *Penicillium janthinellum*, *P. expansum*, *Trichoderma harzianum* and *F. oxysporum*	Good antifungal activity against *Trichoderma harzianum* for all extracts and good antifungal activity against *Penicillium janthinellum* with acetone extracts	Amphotericin B – *A. parasiticus* and *A. niger* - 0.02 mg/ml. Other fungi <0.02 mg/ml.	Mahlo et al. (2016)
45.	*Polystichum pungens* Kaulf Aspidiaceae	*In-vitro*	Fronds Acetone	*Alternaria alternaria* and *Aspergillus niger*	100% growth inhibition	2% Acetone	Afolayan et al. (2002)
46.	*Prunus persica* L. Rosaceae	*In-vitro*	Roots Acetone	*Alternaria alternaria* and *Aspergillus niger*	100% growth inhibition on *Alternaria alternaria*	2% Acetone	Afolayan et al. (2002)
47.	*Quercus acutissima* Carruth. Fagaceae	*In-vitro*	Leaves Water, ethyl acetate and acetone	*F. verticillioides, F. proliferatum*, *F. solani* and *F. graminearum*	Ethyl acetate extract (mg/ml): *F. verticillioides* (0.08), *F. proliferatum* (0.04), *F. solani* (0.04), *F. graminearum* (0.02) Acetone extract (mg/ml): *F. verticillioides* (0.08), *F. proliferatum* (0.04), *F. solani* (0.04), *F. graminearum* (0.02)	Amphotericin B (μg/ml): *F. verticillioides* (2.93) *F. proliferatum* (0.37) *F. solani* (0.37) *F. graminearum* (187.50)	Seepe et al. (2020a)
		In-vivo	Leaves Ethyl acetate and acetone	*Fusarium verticillioides*, *F. proliferatum*, *F. solani*, *F. graminearum*, *F. equiseti*, *F. semitectum, F. subglutinans, F. chlamydosporum*	Not specified	Amphotericin B at 2.5 mg/ml	Seepe et al. (2020b)
48.	*Ricinus communis* L. Euphorbiaceae	*In-vitro*	Leaves Water: methanol (1:1), dichloromethane	*Fusarium graminearum*, *F. verticillioides*, *F. oxysporum*, *Aspergillus parasiticus*, *A. ochraceous*, *A. flavus*	No significant activity	Amphotericin B – *Fusarium graminearum*, *F. oxysporum* – 0.04 gm/ml, *F. verticillioides* - 0.06 mg/ml, *Aspergillus parasiticus*, *A. flavus* – 0.02 mg/ml, *A. ochraceous* – 0.03 mg/ml	Mongalo et al. (2018)
		In-vitro	Leaves Acetone	*Aspergillus flavus*, *Aspergillus ochraceous* and *Fusarium verticilloides*	Good antifungal activity against *Aspergillus flavus*	Amphotericin B – *A. flavus, A. ochraceous* – 0.16 mg/ml F. *verticilloides* – 1.56 mg/ml	Dikhoba et al. (2019)
49.	*Salix capensis* Thunb. Salicaceae	*In-vitro*	Bark and leaves Acetone	*Alternaria alternaria* and *Aspergillus niger*	100% growth inhibition	2% Acetone	Afolayan et al. (2002)
50.	*Schotia brachypetala* Sond. Fabaceae	*In-vitro*	Leaves Water, ethyl acetate and acetone	*F. verticillioides*, *F. proliferatum*, *F. solani* and *F. graminearum*	Water extract (mg/ml): *F. graminearum* (0.04) Ethyl acetate: *F. proliferatum* (0.04) Acetone extract (mg/ml): *F. proliferatum* (0.04)	Amphotericin B (μg/ml): *F. verticillioides* (2.93) *F. proliferatum* (0.37) *F. solani* (0.37) *F. graminearum* (187.50)	Seepe et al. (2020a)
51.	*Schotia latifolia* Jacq. Fabaceae	*In-vitro*	Bark and leaves Acetone	*Alternaria alternaria* and *Aspergillus niger*	100% growth inhibition	2% Acetone	Afolayan et al. (2002)

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Table 2 (*continued*)

No.	Plant species, Family	Test system	Plant part used, solvent (s)	Pathogen(s)/disease(s) managed	Key findings	Positive control	Reference
52.	*Senna didymobotrya* (Fresen.) H. S. Irwin & Barneby Fabaceae	*In-vitro*	Leaves Water, ethyl acetate and acetone	*F. verticillioides*, *F. proliferatum*, *F. solani* and *F. graminearum*	Ethyl acetate (mg/ml): *F. proliferatum* (0.04) *F. solani* (0.08) Acetone extract (mg/ml): *F. verticillioides* (0.08), *F. proliferatum* (0.04), *F. solani* (0.08)	Amphotericin B (μg/ml): *F. verticillioides* (2.93) *F. proliferatum* (0.37) *F. solani* (0.37) *F. graminearum* (187.50)	Seepe et al. (2020a)
53.	*Solanum aculeastrum* Dunal. Solanaceae	*In-vitro*	Leaves Acetone	*Aspergillus flavus*, *Aspergillus ochraceous* and *Fusarium verticilloides*	No significant activity	Amphotericin B – *A. flavus*, *A. ochraceous* – 0.16 mg/ml F. *verticilloides* – 1.56 mg/ml	Dikhoba et al. (2019)
		In-vitro	Leaves Water: methanol (1:1), dichloromethane	*Fusarium graminearum*, *F. verticillioides*, *F. oxysporum*, *Aspergillus parasiticus*, *A. ochraceous*, *A. flavus*	No significant activity	Amphotericin B – *Fusarium graminearum*, *F. oxysporum* – 0.04 gm/ml, *F. verticillioides* - 0.06 mg/ml, *Aspergillus parasiticus*, *A. flavus* – 0.02 mg/ml, *A. ochraceous* – 0.03 mg/ml	Mongalo et al. (2018)
54.	*Solanum mauritianum* Blanco Solanaceae	*In-vitro*	Leaves Water, ethyl acetate and acetone	*F. verticillioides, F. proliferatum*, *F. solani* and *F. graminearum*	Ethyl acetate extract (mg/ml): *F. verticillioides* (0.04), *F. proliferatum* (0.04), *F. solani* (0.04) Acetone extract (mg/ml): *F. proliferatum* (0.04), *F. solani* (0.04), *F. graminearum* (0.04)	Amphotericin B (μg/ml): *F. verticillioides* (2.93) *F. proliferatum* (0.37) *F. solani* (0.37) *F. graminearum* (187.50)	Seepe et al. (2020a)
		In-vivo	Leaves Ethyl acetate and acetone	*Fusarium verticillioides*, *F. proliferatum*, *F. solani, F. graminearum, F. equiseti, F. semitectum*, *F. subglutinans, F. chlamydosporum*	Not specified	Amphotericin B at 2.5 mg/ml	Seepe et al. (2020b)
55.	*Solanum panduriforme* E. Mey. Solanaceae	*In-vitro*	Leaves Water: methanol (1:1), dichloromethane	*Fusarium graminearum*, *F. verticillioides*, *F. oxysporum*, *Aspergillus parasiticus*, *A. ochraceous*, *A. flavus*	Good antifungal activity against *Fusarium graminearum*, *F. oxysporum*, *Aspergillus parasiticus*, *A. ochraceous* with organic solvent.	Amphotericin B – *Fusarium graminearum*, *F. oxysporum* – 0.04 gm/ml, *F. verticillioides* - 0.06 mg/ml, *Aspergillus parasiticus*, *A. flavus* – 0.02 mg/ml, *A. ochraceous* – 0.03 mg/ml	Mongalo et al. (2018)
56.	*Spirostachys africana* Sond. Euphorbiaceae	*In-vitro*	Leaves Acetone	*Aspergillus flavus*, *Aspergillus ochraceous* and *Fusarium verticilloides*	No significant activity	Amphotericin B – *A. flavus*, *A. ochraceous* – 0.16 mg/ml *F. verticilloides* – 1.56 mg/ml	Dikhoba et al. (2019)
57.	*Strychnos mitis* S. Moore Loganiaceae	*In-vitro*	Leaves Acetone	*Aspergillus flavus*, *Aspergillus ochraceous* and *Fusarium verticilloides*	No significant activity	Amphotericin B – *A. flavus*, *A. ochraceous* – 0.16 mg/ml *F. verticilloides* – 1.56 mg/ml	Dikhoba et al. (2019)
58.	*Tagetes minuta* L. Asteraceae	*In-vitro*	Shoot Acetone	*Alternaria alternaria* and *Aspergillus niger*	100% growth Inhibition on *Alternaria alternaria*	2% Acetone	Afolayan et al. (2002)
		In-vitro	Leaves Hexane, dichloromethane and methanol	*Fusarium verticillioides*, *F. proliferatum*	Good antifungal activity against *F. proliferatum* with hexane and methanol extracts. Good antifungal activity against *Fusarium verticillioides* methanol extracts.	Amphotericin B, Cantus – 0.004 mg/ml	Thembo et al. (2010)
		In-vitro	Leaves, flowers and stem Acetone and water	*Xanthomonas campestris* pv. *campestris* causing black rot in rapes	No significant activity	Neomycin (0.2 mg/ml)	Mandiriza et al. (2018)
59.	*Usnea barbata* Web. Usneaceae	*In-vitro*	Whole lichen Acetone	*Alternaria alternaria* and *Aspergillus niger*	100% growth inhibition on *Alternaria alternaria*	2% Acetone	Afolayan et al. (2002)
60.	*Vangueria infausta* Burch. Rubiaceae	*In-vitro*	Leaves Acetone, hexane, dichloromethane and methanol	*Aspergillus niger*, *Aspergillus parasiticus*, *Colletotricum gloeosporioides*, *Penicillium janthinellum*, *P. expansum*, *Trichoderma harzianum* and *F. oxysporum*	No significant activity	Amphotericin B – For *A. parasiticus* and *A. niger* was 0.02 mg/ml after 24 h and 48 h incubation and for the other fungi was <0.02 mg/ml.	Mahlo et al. (2010)

(*continued on next page*)

Table 2 (*continued*)

No.	Plant species, Family	Test system	Plant part used, solvent (s)	Pathogen(s)/disease(s) managed	Key findings	Positive control	Reference
		In-vitro	Leaves Acetone, hexane, dichloromethane and methanol	*Aspergillus niger*, *Aspergillus parasiticus*, *Colletotricum gloeosporioides*, *Penicillium janthinellum*, *P. expansum*, *Trichoderma harzianum* and *F. oxysporum*	No significant activity	Amphotericin B – *A. parasiticus* and *A. niger* - 0.02 mg/ml. Other fungi <0.02 mg/ml	Mahlo et al. (2016)
		In-vitro	Leaves Water, ethyl acetate and acetone	*F. verticillioides*, *F. proliferatum*, *F. solani* and *F. graminearum*	Ethyl acetate extract (mg/ml): *F. verticillioides* (0.08), *F. proliferatum* (0.04), *F. solani* (0.04) Acetone extract (mg/ml): *F. verticillioides* (0.04), *F. proliferatum* (0.04), *F. solani* (0.04)	Amphotericin B (μg/ml): *F. verticillioides* (2.93) *F. proliferatum* (0.37) *F. solani* (0.37) *F. graminearum* (187.50)	Seepe et al. (2020a)
61.	*Vigna unguiculata* (L.) Walp. Fabaceae	*In-vitro*	Leaves Hexane, dichloromethane and methanol	*Fusarium verticillioides*, *F. proliferatum*	Good antifungal activity with hexane, methanol extracts	Amphotericin B, Cantus – 0.04 mg/ml	Thembo et al. (2010)
62.	*Warburgia salutaris* (G. Bertol) Chiov. Canellaceae	*In-vitro*	Leaves Acetone	*Aspergillus flavus*, *Aspergillus ochraceous* and *Fusarium verticilloides*	No significant activity	Amphotericin B – *A. flavus*, *A. ochraceous* – 0.16 mg/ml F. *verticilloides* – 1.56 mg/ml	Dikhoba et al. (2019)
		In-vitro	Leaves Aqueous and methanol (1:1), dichloromethane	*Fusarium graminearum*, *F. verticillioides*, *F. oxysporum*, *Aspergillus parasiticus*, *A. ochraceous*, *A. flavus*	Good antifungal activity against *F. oxysporum*, *Aspergillus parasiticus* with organic solvent.	Amphotericin B – *Fusarium graminearum*, *F. oxysporum* – 0.04 mg/ml, *F. verticillioides* - 0.06 mg/ml, *Aspergillus parasiticus*, *A. flavus* – 0.02 mg/ml, *A. ochraceous* – 0.03 mg/ml	Mongalo et al. (2018)
63.	*Withania somnifera* (L.) Dunal Solanaceae	*In-vitro*	Leaves Water, ethyl acetate and acetone	*F. verticillioides*, *F. proliferatum*, *F. solani* and *F. graminearum*	Water extract (mg/ml): *F. proliferatum* (0.04) Ethyl acetate extract (mg/ml): *F. verticillioides* (0.08), *F. proliferatum* (0.04), *F. solani* (0.08) Acetone extract (mg/ml): *F. verticillioides* (0.08), *F. proliferatum* (0.04), *F. solani* (0.04)	Amphotericin B (μg/ml): *F. verticillioides* (2.93) *F. proliferatum* (0.37) *F. solani* (0.37) *F. graminearum* (187.50)	Seepe et al. (2020a)
		In-vivo	Leaves Ethyl acetate and acetone	*Fusarium verticillioides*, *F. proliferatum*, *F. solani*, *F. graminearum*, *F. equiseti*, *F. semitectum*, *F. subglutinans*, *chlamydosporum*	Not specified	Amphotericin B at 2.5 mg/ml	Seepe et al. (2020b)
64.	*Xylotheca kraussiana* Hochst Achariaceae	*In-vitro*	Leaves Acetone, hexane, dichloromethane and methanol	*Aspergillus niger*, *Aspergillus parasiticus*, *Colletotricum gloeosporioides*, *Penicillium janthinellum*, *P. expansum*, *Trichoderma harzianum* and *F. oxysporum*	No significant activity	Amphotericin B – For *A. parasiticus* and *A. niger* was 0.02 mg/ml after 24 h and 48 h incubation and for the other fungi was <0.02 mg/ml	Mahlo et al. (2010)
		In-vitro	Leaves Acetone, hexane, dichloromethane and methanol	*Aspergillus niger*, *Aspergillus parasiticus*, *Colletotricum gloeosporioides*, *Penicillium janthinellum*, *P. expansum*, *Trichoderma harzianum* and *F. oxysporum*	No significant activity	Amphotericin B – *A. parasiticus* and *A. niger* - 0.02 mg/ml. Other fungi <0.02 mg/ml	Mahlo et al. (2016)
		In-vitro	Leaves Acetone	*Aspergillus flavus*, *Aspergillus ochraceous* and *Fusarium verticilloides*	No significant activity	Amphotericin B – *A. flavus*, *A. ochraceous* – 0.16 mg/ml F. *verticilloides* – 1.56 mg/ml	Dikhoba et al. (2019)
65.	*Zanthoxylum capense* (Thunb) Harv. Rutaceae	*In-vitro*	Leaves Acetone	*Aspergillus flavus*, *Aspergillus ochraceous* and *Fusarium verticilloides*	Good antifungal activity against *Fusarium verticilloides*	Amphotericin B – *A. flavus*, *A. ochraceous* – 0.16 mg/ml *F. verticilloides* – 1.56 mg/ml	Dikhoba et al. (2019)
66.	*Ziziphus mucronata* Wild. Rutaceae	*In-vitro*	Aqueous and 1:1 methanol: dichloromethane leaves extracts	*Fusarium graminearum*, *F. verticillioides*, *F. oxysporum*, *Aspergillus parasiticus*, *A. ochraceous*, *A. flavus*	Good antifungal activity against *Fusarium graminearum* with organic solvent	Amphotericin B – *Fusarium graminearum*, *F. oxysporum* – 0.04 mg/ml, *F. verticillioides* - 0.06 mg/ml, *Aspergillus parasiticus*, *A. flavus* – 0.02 mg/ml, *A. ochraceous* – 0.03 mg/ml	Mongalo et al. (2018)

Table 3
Overview of the genus of plant pathogens investigated in the 16 eligible studies.

Ranking	Genus	[a]Frequency (%) relative to the 16 recorded studies	Examples of diseases caused by the pathogen
1	*Fusarium*	68.75	damping off, crown rot, stem and root rot, vascular wilt (Summerell et al., 2003)
2	*Aspergillus*	43.75	black mould (Al-Sheikh, 2009)
3	*Penicillium*	37.5	green mould (Oshikata et al., 2013)
4	*Colletotricum*	18.75	leaf spot, anthracnose (Solís et al., 2022)
4	*Trichoderma*	18.75	ear rot (Pfordt et al., 2020)
6	*Alternaria*	6.25	leaf blight, black rot, leaf spot, root rot, fruit spot, head rot (Laemmlen, 2002)
6	*Botrytis*	6.25	gray mould (Elad et al., 2007)
6	*Rhizoctonia*	6.25	damping off, necrosis (Patil and Solanki, 2016)
6	*Pythium*	6.25	damping off, soft rot (Smith et al., 2014)
6	*Phytopthora*	6.25	root rot, foot rot, fruit brown rot, damping off (Cacciola et al., 2008)

[a] Frequency (%) = (no. of eligible studies mentioning a genus divided by 16) x 100.

Stem, roots, bark, flowers, leaves and cloves were the plant parts that were evaluated for antifungal activity. However, the leaves (87%) were the most common plant part that was evaluated for its antifungal activity. This could be due to their ease of harvesting and availability relative to other plant parts (Sargin et al., 2015). Leaves also contain phytochemicals which is attributed to the photosynthetic process producing secondary compounds that are effective against diseases (Ampitan, 2013; Ayyanar and Ignacimuthu, 2011; Mugisha-Kamatenesi et al., 2008). Different solvents were used for extraction purposes including acetone, ethyl acetate, water, methanol, hexane, dichloromethane, carbon tetrachloride, diethyl ether, chloroform and ethanol. Acetone (69%) was the most common solvent used, while carbon tetrachloride, diethyl ether, and chloroform (each 6%) were the least used solvents. Acetone dissolves many lipophilic and hydrophilic components. It is volatile with low toxicity and miscible in water. Based on existing evidence, acetone is viewed as the best extractant for antimicrobial compounds from plants (Eloff, 1998b; Kotze and Eloff, 2002). Amphotericin B, neomycin and 2% acetone were used as positive controls against the fungal pathogens. However, Amphotericin B (69%) was the widely used positive control.

Information such as the assay-type, plant part used, solvent used and inclusion of controls are important when analysing antimicrobial results. However, some studies lacked information on assay-type (Hlokwe et al., 2018, 2020) and controls (Eloff et al., 2017; Hlokwe et al., 2018, 2020; Mnacube, 2021) . This often makes the interpretation and analysis of the data inconclusive (Othman et al., 2011; Weckerle et al., 2018). Based on the key aspects investigated in this current review, 11 of the screened studies provided sufficient information making their analyses conclusive. For instance, the authors clearly provided justification for the selection of the plants and detailed description of the applied methods. The authors also provided the relevance of the phytopathogens that were investigated against, as well as including comparable positive controls (Heinrich et al., 2020).

3.4. Examples of plants with potential for crop protection against phytopathogens

Approximately 79% of the screened plants demonstrated promising antifungal activity (MIC value = 0.1 mg/ml) against phytopathogens, which is an indication of their potential in managing microbial-related diseases in plants. For instance, acetone extracts of *Breonadia salicina* leaves had strong antifungal activity against *Penicillium janthinellum* (MIC of 0.08 mg/ml) (Mahlo and Eloff, 2014), while acetone extracts of *Markhamia obtusifolia* leaves displayed strong antifungal activity against *Aspergillus flavus* (MIC of 0.08 mg/ml) and *Fusarium verticilloides* (MIC of 0.08 mg/ml) (Dikhoba et al., 2019). Acetone extracts of *Grewia occidentalis* twig and leaves exerted 100% growth inhibition on *Alternaria alternaria* (Afolayan et al., 2002), while methanol extract of *Moringa oleifera* leaves supressed the growth of *Rhizoctonia solani* and *F. oxysporum* f. sp. *lycopersici*. The highest pathogen growth suppression was obtained at a concentration of 6 g/ml (Hlokwe et al., 2018, 2020). However, 14 plants did not exert significant antifungal activity against the tested phytopathogens. These plants included *Aloe ferox*, *Apodytes dimidiata*, *Artemisia afra*, *Brachylaena discolour*, *Capparis tamentosa*, *Chlorophytum comosum*, *Ficus natelensis*, *Heteromorpha arborescens*, *Kirkia wilmsii*, *Lavandula angustifolia*, *Strychnos mitis*, *Spirostachys africana*, *Solanum aculeastrum* and *Xylotheca kraussiana*.

In this review, we identified *Breonadia salicina*, *Harpephyllum caffrum*, *Lantana camara*, *Moringa oleifera*, *Tagetes minuta* and *Vangueria infausta* as the most screened plants. They also displayed significant antifungal activity against most phytopathogens (represented by at least 3 studies with =2 phytopathogens) (Table 2). For instance, leaf extracts of *L. camara* demonstrated strong antifungal activity against *F. verticilloides* (MIC of 0.04 mg/ml), *F. proliferatum* (MIC of 0.04 mg/ml), *F. graminearum* (MIC of 0.08 mg/ml) and *F. solani* (MIC of 0.04 mg/ml) (Seepe et al., 2020a). Shoot extracts of *T. minuta* demonstrated 100% growth inhibition against *A. alternaria* (Afolayan et al., 2002), while the

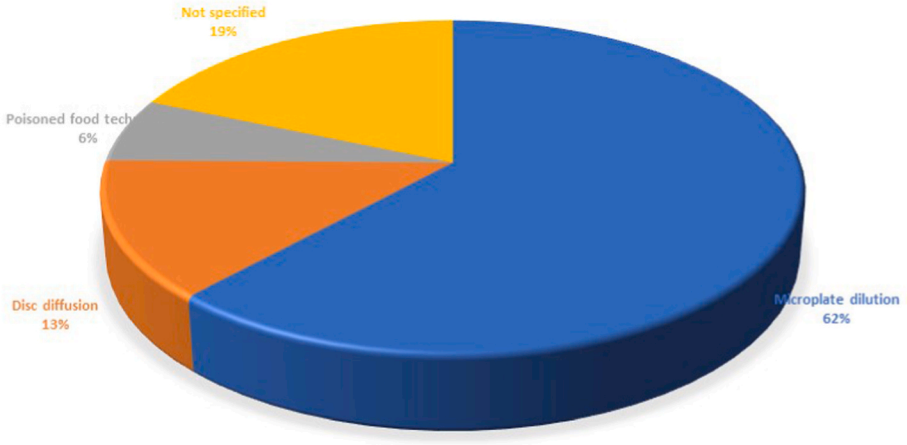

Fig. 3. A representation of antimicrobial method assays of plants used in managing microbial-related plant diseases in South Africa (n = 16).

leaf extract had strong antifungal activity against *F. proliferatum* (MIC of 0.08 mg/ml) and *F. verticilloides* (MIC of 0.02 mg/ml) (Thembo et al., 2010). Studies beyond South Africa have supported the potential of *M. oleifera* against phytopathogens. In the study by Oniha et al. (2021), there was significant inhibition of fungal development against *Aspergillus niger*, *A. fumigatus*, *A. flavus*, *Rhizopus* spp., *Penicillium* spp., and *Trichoderma* spp. by aqueous extract of *M. oleifera* leaves. It was found that the antifungal activity *M. oleifera* was either higher than or equal to commercially available fungicide, ketoconazole. Besides having antifungal effects against phytopathogenic fungi, studies have reported antibacterial activities of *M. oleifera* extracts. The study by Arredondo-Valdés et al. (2021) demonstrated significant inhibitory effect of ethanol extracts of *M. oleifera* leaves against *Agrobacterium tumefeciens*, *Clavibacter michiganensis* subsp. *michiganensis*, *Pseudomonas syringae* pv. *tomato*, *Ralstonia solanacearum* and *Xanthomonas axonopodis*. From their findings, *M. oleifera* was recommended as a potent bio-bactericide. Fontana et al. (2021) reported significant inhibitory effect of methanolic, hydroalcoholic and hydroalcoholic maltodextrin extracts of *M. oleifera* leaves which exhibited bacteriostatic and bactericidal effects against *Xanthomonas campestris* pv. *campestris*.

Beyond South Africa, the antimicrobial potential of *T. minuta* against phytopathogens has been explored. For instance, Aloo et al. (2019) reported the potential of aqueous extracts of *T. minuta* leaves, bark, roots and flowers, in managing crop diseases caused by *Erwinia chrysanthema*, *Ralstonia solanacearum* and *F. oxysporum* including tomato wilt disease. All the extracts exhibited good antimicrobial activity against all the pathogens. However, the most promising antifungal effect was observed against *R. solanacearum*. Likewise, *T. minuta* exhibited antibacterial properties against *E. chrysanthema* (Aloo et al., 2019). In the study by Kwamboka et al. (2016), aqueous extracts of *T. minuta* leaves and stem had strong antibacterial activity against *Pectobacterium carotovorum*, which is known to cause vascular wilt and soft rot in vegetables. Moreover, *T. minuta* showed inhibition zones of 6.1 mm, 6.667 mm and 7.167 mm at 20%, 30% and 40%, respectively. These three inhibition zones from the applied concentrations were similar to that recorded by streptomycin sulphate (8.83 mm), the positive control used in the assay. These medicinal plants could be relevant in addressing the issue of food security as several studies revealed their promising antimicrobial activity against various phytopathogens causing diseases in economical important crops.

4. Conclusions

Currently, studies on the utilisation of medicinal plants for the management of phytopathogens are limited in South Africa. It is evident that botanicals have the potential to be used in the management of microbial-related diseases in plants as observed from the various antimicrobial activity assays. Most of the antimicrobial activity studies on medicinal plants in the reviewed articles targeted fungi. In the current review, a total of 66 plants (44 families) were screened for their antifungal activity against diverse phytopathogens. Selection of these botanicals was mostly based on previous literature studies exploring the antifungal activity of the plants against human or animal pathogens rather than ethnobotanical studies. These studies can serve as baseline for development of plant-based fungicides and pesticides. More attention needs to be directed towards ethnobotanical studies as they are currently limited. Rational antimicrobial screening of the medicinal plants should follow as well, establishing the MIC and the minimum bactericidal or fungicidal concentration (MFC or MBC). It is known that MFC or MBC assays demonstrate the killing effects of the plant extracts, an indication of reduced possibility of antimicrobial resistance. Future antimicrobial studies should also focus on plant diseases caused by bacteria and viruses.

Authors contributions

Conceptualization, J. LM.; W.O.M. and A.O.A.; methodology, J.L.M.; investigation, J.L.M and A.O.A.; resources, A.O.A. and W.O.M.; writing—original draft preparation, J.L.M.; writing—review and editing, A.O.A., W.O.M. and B.P.K.; supervision, A.O.A., W.O.M. and B.P.K.; project administration, A.O.A.; funding acquisition, W.O.M. and A.O.A. All authors have read and agreed to the published version of the manuscript.

Funding

This research was funded by National Research Foundation of South Africa, grant number 135452 awarded to WOM. AOA received funding from the National Research Foundation of South Africa (Grant no: SRUG2204224395).

Declaration of competing interest

The authors declare no conflict of interest.

Data availability

Data will be made available on request.

Acknowledgments

We express our thanks to the North-West University for providing post graduate support to James Mwinga during this PhD study. Institutional support from the North-West University, University of Mpumalanga, University of KwaZulu-Natal and Dohne Agricultural Development Institute is appreciated. We also express our thanks to Melia Bokaeng Bonokwane for the valuable discussion and guidance during the literature search and collation.

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