

REVIEW

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Plant active products and emerging interventions in water potabilisation: disinfection and multi-drug resistant pathogen treatment

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Abstract

Background: This review aims at establishing the emerging applications of phytobiotics in water treatment and disinfection.

Results: Statistical analysis of data obtained revealed that the use of plant product in water treatment needs more research attention. A major observation is that plants possess multifaceted components and can be sustainably developed into products for water treatment. The seed (24.53%), flower (20.75), leaf (16.98%) and fruit (11.32%) biomasses are preferred against bulb (3.77%), resin (1.89%), bark (1.89%) and tuber (1.89%). The observation suggests that novel applications of plant in water treatment need further exploration since vast and broader antimicrobial activities (63.63%) is reported than water treatment application (36.37%).

Conclusions: This review has revealed the existing knowledge gaps in exploration of plant resources for water treatment and product development. Chemical complexity of some plant extracts, lack of standardisation, slow working rate, poor water solubility, extraction and purification complexities are limitations that need to be overcome for industrial adoption of phytochemicals in water treatment. The field of phytobiotics should engage modern methodologies such as proteomics, genomics, and metabolomics to minimise challenges confronting phytobiotic standardisation. The knowledge disseminated awaits novel application for plant product development in water treatment.

Keywords: Microbial resistance, Phytochemicals, Water treatment, Standardisation

Introduction

Although plant products are available [1–3] and exhibit different mechanisms of action from conventional antimicrobials [4, 5], there are critical gaps in the exploration of plant resources [6] for development of useful products [7]. The variation and complexity in chemical compositions of plants potentiate their activity [5]. Different phytochemicals present in plants such as phenols, quinones, flavonols, tannins, coumarins and alkaloids are responsible for plant activities. Flavonols and phenolics

have been reported for their antioxidant activity exerted by scavenging the ‘free-oxygen radicals’ thereby giving rise to a fairly ‘stable radical. Cinnamaldehyde and other polyphenols have been known for their anti-diabetic activity by enhancing the amount of insulin-like TTP (Thrombotic Thrombocytopenic Purpura), IR (Insulin Resistance), and GLUT4 (Glucose Transporter-4) in 3 T3-L1 Adipocytes. Phenolic acids are known for their antimicrobial activity by reduction of adherence of organisms to cells and essential oils for their anti-inflammatory effect by suppressing nitric oxide production [8, 9].

Current interventions of plants dealing with microbial resistance, immunomodulation, as antitumour agents,

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maintenance of illnesses affecting immune systems and in microbial virulence attenuation have been described in various researches [10–13]. In the early days of use, plants were used in their crude state [14] and contribute greatly to the health care system of local communities [15]. Ethnomedicinally, plants have found application in the treatment of several diseases and ailments. Examples are *Astragalus membranaceus*, roots of *Trichosanthes kirilowii*, roots and rhizomes of *Panax quinquefolius* and pulps of *Cornus officinalis* reported for treatment of diabetes mellitus.

Terminalia chebula and *Adenocarpus mannii* are known for their immunomodulation properties [16, 17], *Thea assamica* in the treatment of impetigo [18], *Ocimum gratissimum* in the treatment of acne [19], *Drechslera rostata* and *Polygala molluginifolia* for their antitumor activities [20, 21]. Medicinal plants including *Ageratum conyzoides*, *Celosia trigyna*, *Centella asiatica*, *Brassica nigra*, *Racunculus oreophytus*, *Azadirachta indica*, *Ficus exasperate*, *Senna hirsuta*, *Morus alba*, *Artocarpus heterophyllus* have all been reported for their ethnomedicinal use in various ethnic groups [22–24].

Microbial resistance has increased with drug discovery resulting in serious health concerns globally [25, 26] and indiscriminate use of antimicrobial remains the main cause [27]. Therefore, the emergence of multidrug resistant microbes in water and undesirable effects of conventional antimicrobials call for alternative means of water treatment of plant origin [28]. Various microbial contamination of human origin in water may be controlled by extracts of plants [29]. In Kirui et al. [30]. Aqueous extract of *Acacia nilotica*, *Acacia seyal*, *Acacia tortilis*, *Acacia etbaica*, *Albizia anthelmintica*, *Euclea divinorum* and *Plumbago zeylanica* were investigated for their water treatment capacity and report indicates a notable effect. Extracts of *Moringa oleifera*, *Jatropha curcas* and *Guar gum* have also been investigated for their water treatment potential and reduction in turbidity of the treated water was observed [31]. These observations show the potential of plant product for water treatment. This attempts made to finding alternative way to combat resistant microorganisms and water disinfection is noble. It is of low cost and mostly available for safe water especially, in Africa. This review discusses the prospects of plant and plant products in less reported areas of water and antimicrobial resistance interventions.

Methodology

A desktop structured study of scholarly published articles was employed in the study of over 200 relevant literatures. The searched databases included Science Direct, Google Scholar and Web of Science. The searched terms and keywords included history, types, mechanisms of action, standardisation and application of phytobiotics in

various fields. The search was restricted to articles written in English language and covered the period between 1993 and 2020. A review of studies reporting the use of plants as alternative against resistant microorganism especially in water treatment was attempted. Studies reporting the mechanisms of action of phytobiotics, methods employed in standardisation of herbal drug and current existing challenges in this field were examined. Raw information obtained were computed in MS-excel 2016 to convert data into processed statistics for the interpretation of the data. Tables, figures charts and simple percentages were used to present and interpret the results of data.

Results and discussion

Classification of synthetic and plant-based antimicrobials

The treatment of microbial infections and contamination has mainly involved the use of antimicrobial agents like antiseptics, sanitizers, disinfectants, as well as antibiotics [32]. Antibiotic could specifically denote a substance with the capacity to inhibit, that is, cause static or cidal effect to microbes at low concentrations [33]. Pharmaceutical agents such as antibacterial, antifungal, antiviral, and antiparasitic drugs are broadly referred to as antibiotics [34]. Among the several classification schemes for antibiotics, those based on the molecular structures, spectrum of activity and modes of action [35] are more preferred as indicated in Table 1. Antibiotics can also be classified as injectable, oral or topical based on route of administration. Antibiotics with similar structure will usually exhibit similar trends of actions and effects.

The antimicrobial activity of plants has been credited to the existence of phytochemicals in specific parts of plants [38] where they contribute to enhanced plant's survival by warding off pathogenic microorganisms [39, 40]. Some major groups of antimicrobials derived from plants include saponins, polyphenols, alkaloids, lectins, tannins, flavonoids, and terpenoids [41]. Synthetic pathways of some phytochemicals and related enzymes are indicated in Fig. 1.

Basic phenolic acids and phenols

These are made of mono-substituted ring of phenol [43]. It is thought that the site(s) as well as numbers of hydroxyl components in this group influence the level of toxicity against microorganisms as it is evident that higher hydroxylation correlates with improved toxicity [44]. When phenolics possess a lower level of oxidation and a C₃ side chain, it is referred to as an essential oil [45]. This group includes cinnamic acids, caffeic acids, and pyrogallol with proven toxicity against microbes. The defensive functions of phenolic compounds in plants include antimicrobial activities as well as cell wall repair and strength [46].

Table 1 Existing groups of antibiotics and their characteristics

Molecular structure	Action site/target	Spectrum of activity
Beta-lactams	Cell wall	Wide, Narrow
Quinolones	Nucleic acid synthesis	Narrow
Sulfonamides	Cell metabolite synthesis	Wide
Aminoglycosides	Cell Protein production	Narrow, Wide
Oxazolidinones	Cell protein production	Wide
Glycopeptides	Cell wall synthesis	Narrow
Macrolides	Cell protein production	Wide
Tetracyclines	Inhibition of protein synthesis	Broad

Source: [36, 37]

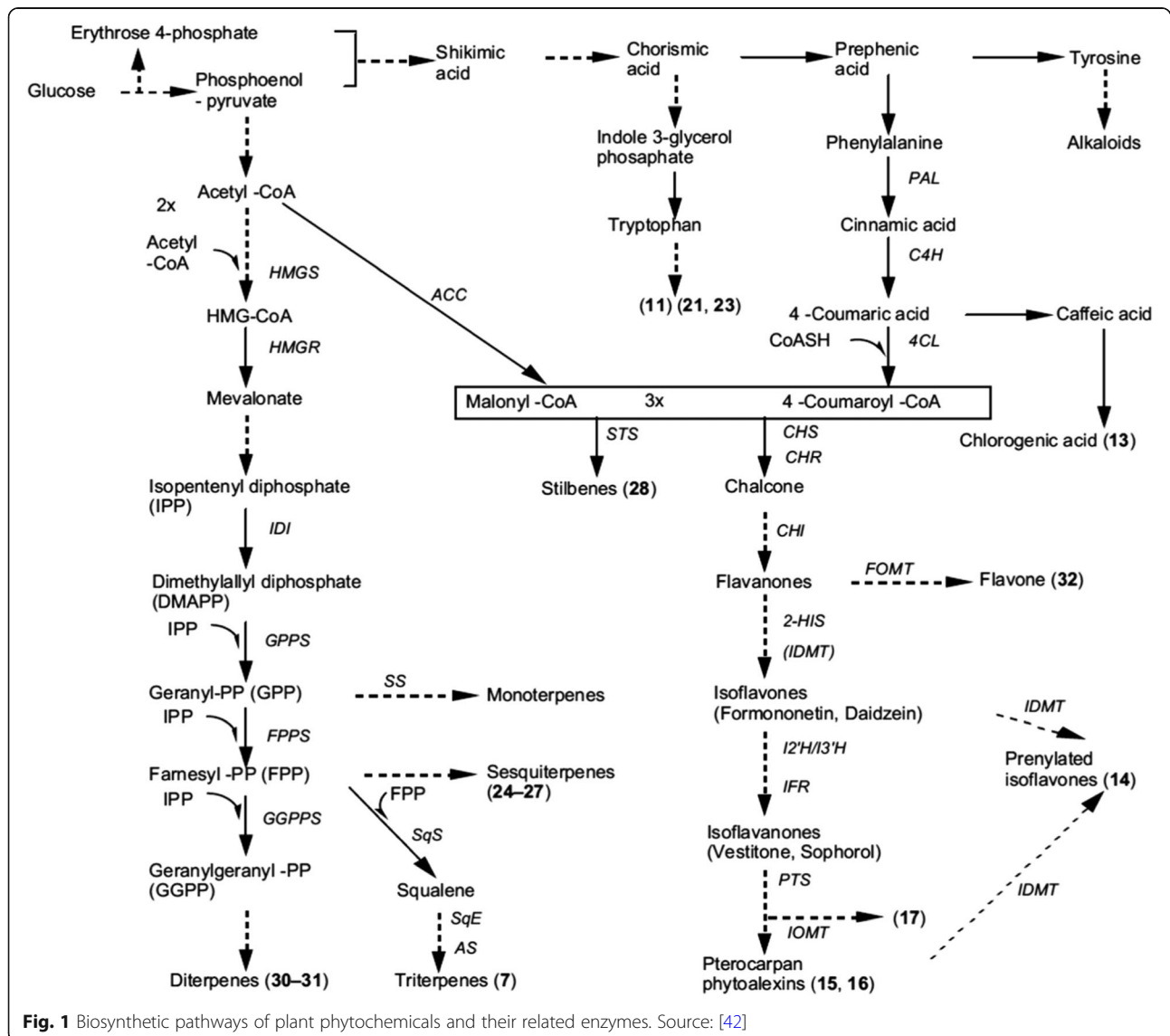


Fig. 1 Biosynthetic pathways of plant phytochemicals and their related enzymes. Source: [42]

Quinones

These are classes of cyclic organic compounds with two carbonyl groups characterised with high reactivity and ubiquity. They possess aromatic rings and 2 ketone substitutes viewed as an important phytochemical group and possess excellent antimicrobial activities [5]. Quinones are responsible for the natural activity of browning reaction on plant. In microbial cell, quinones target surface-exposed adhesins, membrane bound enzymes and cell wall polypeptides [45]. Quinones may as well render substrate unavailable to microorganisms. An example is anthraquinone with a wide spectrum of antimicrobial actions [5].

Flavonols and flavones

These classes of flavonoids possess a double bond between position 2 and 3, and oxygen (a ketone group) in position 4 of the C ring (Fig. 2). Flavones have demonstrated excellent antibiosis against broad groups of microbes [47]. Reported antiviral and other bioactive effects of these groups of phytochemicals include the action of herperetin, galangin and alpinumisoflavone

against Human Immunodeficiency Virus, poliovirus type 1, gram positive bacteria, fungi, and schistosomal infections [46].

Tannins

Tannins are poly-phenolics with wide distribution in various plant parts and are involved in many physiological activities of plant such as stimulation of phagocytic cells and anti-infective activities [47]. The antibacterial activities of tannins are attributed to their capacity to disrupt bacterial enzymes, cell envelope, adhesins and transport proteins. They are toxic to fungi, bacteria and yeasts cells [5]. Their strong affinity for iron on cell membrane results in inactivation of membrane-bound protein, which is responsible for wide antibacterial activities of gallotannin containing plants [49].

Coumarins

These are phytochemicals with bonded alpha pyrone and benzene. Coumarins may exhibit selective antiviral effects. Warfarin is a commonly reported coumarin which produces diverse biological activities and has been

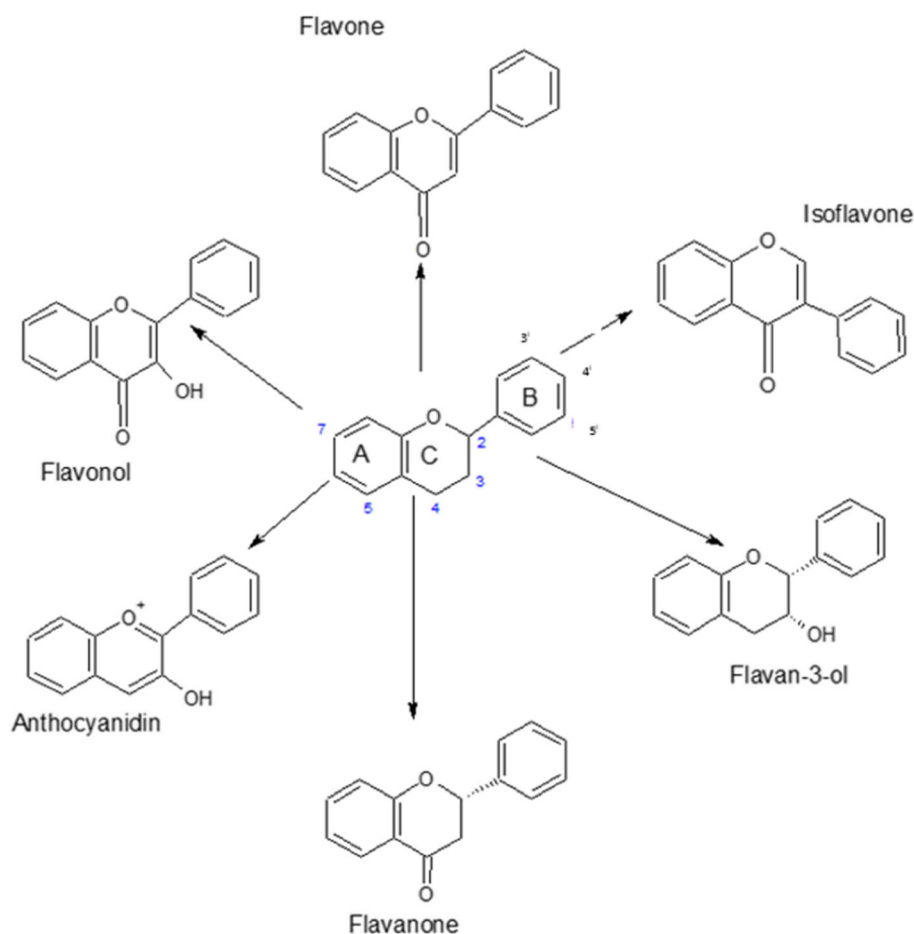


Fig. 2 Structure of flavonoids [48]

proved in-vitro to inhibit the growth of *Candida albicans* [47]. They can stimulate macrophages and reduce tenacity of microbial infection. Warfarin has also been a prescribed drug therapy for prevention of thromboembolic conditions for decades [50]. Esculetin, 6-nitro-7-hydroxycoumarin, scopoletin, 7,8 -dihydroxy-4-methylcoumarin have also been reported for cytotoxicity activity against cancer cell lines [51].

Alkaloids

Alkaloids are nitrogenous heterocyclic compounds. The first medically engaged alkaloid- morphine, was obtained from *Papaver somniferum*. This group of phytochemicals proved to be microbiocidal (against *Entamoeba* spp. and *Giardia*) and are antidiarrheal. Examples of alkaloids include diterpene alkaloids, berberine (isoquinoline alkaloid) and solamargine (glycoalkaloid) used against a wide range of fungi, protozoa, bacteria, viruses and in maintenance of HIV [5, 52]. They penetrate cells, intercalate DNA and target several nucleic acid enzymes, resulting in severe damages to microbial cells [53].

Emerging interventions of phytobiotics

Intervention in water treatment

The use of plant derivatives as microbial inhibitors has been greatly reported [54–57]. However, limited literatures exist on the application of plant as disinfectants in water treatment. Winward et al. [58] reported the antimicrobial activity of 8 mixtures of different plant extracts which were studied for disinfection of coliform in grey water. Another study using thyme oils recorded higher inactivation of *E. coli* when compared to chlorinedioxide and ozonation for disinfection of water [59]. Extracts of plants such as *M. oleifera*, *J. curcas*, Guar gum [60], *Terminalia glaucescens*, *Zanthoxylum zanthoxyloides*, *Gongronema latifolium* [61, 62], *Azadirachta indica* oil extracts [63] and *Luffa cylindrica* fruit extracts [64] have been reported for use in water treatment. It must be noted that high concentrations of crude plant extracts are not desired in water treatment since they result into undesired amount of suspended solids and contribute to taste and colour development. Hence, purified active plant-derived compounds rather than crude extracts or powders are preferred for water treatment.

Interventions in microbial resistance

Arctostaphylos uvaursi, *Vaccinium macrocarpon*, *Hydrastis canadensis* as well as oil extracts of *Melaleuca alternifolia* and *Echinacea* species have been used for the treatment of microbes of urinary tract, skin and lung origin [56, 65]. Curative potential of plant extracts has been investigated and developed as novel drugs to control microbial infections and those with minimum

inhibitory concentration of 100–1000 mg/ml are accepted and classed as antimicrobials [56]. Reports by various investigators had confirmed the antimicrobial potency of different plant materials [66]. Plants like *Holarrhenea antidyssentrica* [67], *Tapinthus sensillifolius* [68], *Psidium guajava*, *Mangifera indica* [69], *Rauelfia tetraphylla*, *Physalis minima* [70], *Salvia* spp. [71] and *Salicornia brachiata* [72] have demonstrated antimicrobial effects.

Plant products have been considered as alternatives to synthetic counterparts with significant results, including commercial antiseptics [73], sanitisers [74] and antibiotics [75]. Several other plant materials and formulations have been tested against different bacterial and fungal isolates with satisfactory results in literature [76–79]. Furthermore, plants active compounds have been considered useful in cases of multidrug resistance [80] and inhibition of biofilm formation [81]. Selected plants bioactivities against multi-drug resistant microbes are presented in Table 2. They have been considered for their effects in efflux pump inhibition [82]. Fungi as well as bacteria have all been treated by several plant compounds, reducing their virulence and pathogenicity through modulation of gene transcription, expression of proteins and quorum sensing [83–89].

Plant products are also considered in adjuvant application. Since phytochemicals possess varied minimum inhibitory concentrations (MIC) from synthetic antibiotics, phytochemicals may be a good adjuvant for potentiating the activities of conventional biocides to improve efficacy and reduce the dosage of synthetic disinfectants [93, 94]. Many reviews have dealt with reports on system of actions of plant materials and extensive list of herbs with antimicrobial activity exists [95–105]. Some examples of interventions of phytobiotics as antimicrobial are presented in Table 3.

Mechanisms of action of antibiotics and phytobiotics

Diverse mechanisms exist to define the actions of phytochemicals in different bioactivities. They may prevent the growth of microorganisms, interfere with some biological metabolic processes or may modulate signal transduction and gene expression pathways [110–112]. Multiple molecular targets of phytochemicals have been identified to include cell cycle proteins, cell adhesion molecules, protein kinases, transcription factors and cell growth pathways [113–115]. Multi-molecular targets of plant phytochemicals account for multi-mechanisms of action in plant product [116]. Phytochemicals may modulate transcription factors [117], redox-sensitive transcription factors [118], redox signalling, and inflammation.

The general antimicrobial activities of conventional antimicrobials are hinged on inhibition of several cellular

Table 2 Overview of extracts with efficacy against resistant microorganisms

Extract types	Record against resistant microbes
Alpha mangostin from <i>Gracinia mangostana</i>	Vancomycin resistant enterococci (VRE)
Ethanol extract of <i>Ocimum gratissimum</i> , <i>Vernonia amygdalina</i> , <i>Zingiber officinale</i> ,	MDR <i>E. coli</i> , <i>S. aureus</i> , <i>P. vulgaris</i> , <i>B. subtilis</i> , <i>S. typhimurium</i>
Methanolic extracts from <i>Boswellia papyrifera</i> , <i>Caesalpinia coriaria</i> , <i>Psidium guajava</i> , <i>Commiphora molmol</i> and <i>Centratherum punctatum</i>	<i>Klebsiella pneumonia</i> , MDR <i>Staphylococcus aureus</i> , Methicillin-resistant <i>Staphylococcus aureus</i> (MRSA), MDR <i>Acinetobacter baumannii</i>
Ethanol extracts of <i>Pelargonium sidoides</i> , <i>Acacia nilotica</i> , <i>Cinnamomum zeylanicum</i> , <i>Syzygium aromaticum</i> , <i>Allium sativum</i> and <i>Cinnamomum cassia</i> .	<i>A. niger</i> , <i>E. coli</i> , <i>K. pneumoniae</i> , <i>Candida albicans</i> , Extensively drug-resistant (XDR) <i>M. tuberculosis</i> and Multi-drug resistant <i>Pseudomonas aeruginosa</i>
Alkaloid fraction of <i>Prosopis juliflora</i>	<i>Acinetobacter</i>
Methanolic and ethanol extracts of <i>Chromolaena odorata</i>	MDR <i>S. aureus</i> , <i>P. aeruginosa</i> , <i>K. pneumoniae</i>
Aqueous extract of <i>Thonningia sanguine</i>	ESBL-producing <i>E. coli</i>
Aqueous extract of <i>Allium sativum</i>	MDR <i>S. aureus</i> , <i>S. epidermidis</i> , <i>S. pneumoniae</i> , <i>S. typhi</i> , <i>E. coli</i>
Ethyl acetate extracts of <i>C. punctatum</i>	MDR <i>Acinetobacter baumannii</i>

Source: [80, 90–92]

functions and structure, including cell membrane function, cell wall synthesis, nucleic acid and protein synthesis, as well as blockage of key metabolic pathways. Phytochemicals act majorly by collapsing cell walls and membranes, resulting in leakage of the cell component, interruption of proton motive force, dysfunction of efflux pump and enzymes, all leading to cytolysis [119]. Some phytochemicals inhibit or minimise quorum sensing and this signifies a feasible method of countering antibiotic resistance in microorganisms since quorum sensing is partly involved in the mechanism of antibiotic-resistance in microbes [120].

A group of cell membrane disruptors include amphotericin B, polyenes, imidazole, triazole and polymyxins [36]. This group disrupts the structure of the membrane in cytoplasm of microorganisms resulting in the escape of macromolecules and ion from the cell, which results in lethal effects [121]. Antibiotics inhibiting cell wall synthesis are vancomycin, bacitracin, penicillin and cephalosporin. These antibiotics manipulate specific steps in homeostatic cell wall biosynthesis, in inhibition of peptide bond formation reaction catalysed by transglycosylase and transpeptidases and then activation of autolytic

enzymes [122]. Antibiotics can block nucleic acid replication and halt transcription by inhibition of DNA polymerase, helicase or RNA polymerase. Examples are rifampin, trimethoprim, quinolones and sulphonamides [37, 123].

Antibiotics inhibiting protein synthesis may either block the initiation of protein translation or peptidyl tRNAs translocation, which inhibit peptidyltransferase reaction involved in elongating the nascent peptide chain [124]. Examples of protein inhibiting antibiotics are chloramphenicol, tetracycline, erythromycin, lincomycin, and aminoglycosides. Some antibiotics like sulphonamides and trimethoprim mimic important substrate needed for cellular metabolism in microbes. This deception results in microbial enzyme attachment to antibiotic rather than the needed substrate [125] resulting in blockages of key metabolic pathways of survival. An example of metabolic pathway blocking antibiotics is sulphonamides, which are structurally identical to *p*-aminobenzoic acid needed in the synthesis of folic acid, thus disrupting the nucleic acid synthesis and amino acid production, since they imitate materials needed for folic acid metabolism [125].

Table 3 Medicinal plants and their antimicrobial intervention

Botanical names	Activity	References
<i>Tuberaria lignosa</i>	Antiviral activity	[10]
<i>Cymbopogon citratus</i>	Antibiofilm activity	[81]
<i>Rauvolfia vomitona</i>	Efflux pump inhibition	[82]
<i>Cymbopogon citratus</i>	Antibiofilm activity	[105]
<i>Berberis aristata</i>	Microbial virulence attenuation	[106]
<i>Chromolaena odorata</i>	Adjuvant therapy	[107]
<i>Mangifera indica</i>	Adjuvant therapy	[108]
<i>Andrographis paniculata</i>	Antiral activity	[109]

Conventional chemically synthesised antibiotics and phytobiotics significantly differ with respect to frequency in spatial arrangement and radical composition [126]. The latter is with less nitrogen, phosphorus, sulphur, halogens and exhibit diverse and enhanced scaffold formation, stereo-chemical conformation, molecular complexity, varied ring system and carbohydrate compositions [127]. Furthermore, phytochemicals can disrupt protein-protein reactions and act as immune modulators and modulators of mitosis with less resistance from microbes due to the aforementioned complexity of plant phytochemicals [128]. Plant phytochemicals therefore exert activities via highly complex and diverse mechanisms, including disruption in cell quorum sensing, membranes, structures, nucleic acid synthesis, cytoplasmic material and cell metabolism [129–133]. A common phenomenon is that several compounds in crude plant extract act at different target sites in pathogens and contribute to optimum efficacy of plant extracts. Phytochemicals may exhibit antimicrobial effect in microbes not only through direct lethal activity, but also by altering key events in pathogenesis [134].

Standardisation of phytobiotics

Herbs comprise of crude plant materials such as fruits, flowers, stems, wood, leaves, seeds or other parts of plants in whole or parts. Herbal products are prepared through different carefully selected processes of solvent extraction and purification, and more recently by novel advanced instrumentation techniques by physical, chemical and biological processes alone or in combination with conventional extraction process. Products which have been modified with synthetic compounds or other chemically defined, active substances as well as isolated

constituent from herbal materials may not wholly be accepted as herbal [135].

Standardisation in phytomedicine refers to the procedure for ensuring quality, standard characteristics, persistent nature and absolute quantifiable values with a guarantee of effectiveness, non-toxicity, excellence and reproducibility [136]. Validation of herbal drugs and recognition of counterfeits from quality herbal products are necessary for public health and quality reproducibility in herbal medicine. Standardisation reduces batch differences, guarantee effectiveness, originality, safety and acceptability of herbal products [137]. Some recent techniques of herbal standard verification include Thin Layer Chromatography, High Performance Thin Layer Chromatography, Gas Chromatography, Super Critical Fluid Chromatography, Chromatographic Fingerprinting and DNA Fingerprinting. Brief details on herbal drug standardisation are given in Table 4.

Studies on commercial disinfectant for water treatment

When choosing a disinfectant for water processing, there is a need to consider if it follows all regulatory approvals [146]. Through the use of disinfectants, pathogenic (resistant) bacteria present in water can be destroyed to make water safe for drinking [147]. Plant disinfectants have also been produced as alternative to the chemical disinfectant counterparts. Tannins, plant gums and celluloses are examples of plant products that have been reported as effective natural disinfectants [148, 149]. Tannins are produced from polyphenolic metabolites from bark, fruits and leaves of plants [150]. Mimosa bark tannin, quebracho wood tannin, pine bark tannin and eucalyptus species bark tannin are common tannins used in for water treatment. The coagulation effect of tannins have been tested for the treatment of raw water in the

Table 4 Various techniques for herbal drug analysis

Method	Application
Thin Layer Chromatography	Used in the assessment of herbal drugs, TLC is commonly engaged [138] since it allows rapid analysis with easy sample preparation need. It supplies semi-quantitative and qualitative details and may provide information on quantity and composition of phytochemicals [139].
High Performance Thin Layer Chromatography:	This is usually engaged to study compounds with less polarities. It is commonly used for identification and recognition of counterfeit products and assists in quality control of herbal and health products [140].
Gas Chromatography:	The basis of gas chromatography separation is the redistribution of compounds between a support stationary and gaseous mobile phase material. Gas chromatography is greatly in use to separate and identify volatile phytochemicals in plant materials [141].
Super Critical Fluid Chromatography	This technique combines the features of gas and liquid chromatography. It handles processing of compounds that cannot be easily determined by conventional gas and liquid chromatography [142].
Chromatographic Fingerprinting	When similar herbal drugs are developed from similar chemical component but possess different identifiable chemical characteristics, chromatographic fingerprinting can be used to resolve the differences. It uses chromatography profiles obtained from extracts' chemical components to establish similarities and differences between plant products. The validation and identification of herbal products can be perfectly resolved even when the chemical constituents are difficult to handle in complex situations [143].
DNA Fingerprinting	This is an important tool engaged when phytochemically unresolvable adulterated parts of plant are used in imitation for the genuine products. The availability of intact genomic DNA from plant samples after processing is the key for using DNA fingerprinting to resolve processed drug samples with unresolvable phytochemical similarities [144, 145].

removal of suspended and colloidal materials, removal of dyes, pigments as well as inks from ink-containing wastewater [151, 152].

Flocculants have also been derived from several plants gums and mucilages. These are obtained after aqueous extraction, precipitation with alcohol and drying. It has been used in the treatment of landfill leachate, textile wastewater, tannery effluent and sewage effluent [153, 154]. From the report from Agarwal et al. [155], result showed 85% removal of suspended solids and 90% colour removal using these plant-based products. Cellulose is another alternative to synthetic disinfectant in water purification. Its water purification effect is due to the abundant free –OH groups on the chain that enables the removal of metal ions and organic matter from water [156]. However, the use of cellulose is limited because of its poor solubility and low chemical reactivity. This disadvantage can be taken care of by carboxymethylation [157].

Commercially, Tanfloc have been produced by a Brazilian company, and TANAC from the bark of Acacia tree [158]. Tanfloc allows for the removal of biological oxygen demand and chemical oxygen demand and generates a sludge volume that is biodegradable. Tanfloc has been tested to remove heavy metals from polluted surface water and municipal wastewater [150]. Another company in Italy, Silvateam also produced a commercially available plant based disinfectant called SilvaFLOC from the bark of *S. balansae*. Silvafloc has been tested on surface river water and has been reported safe for use in drinking water treatment [159]. It is found to be more efficient than aluminium sulphate for water clarification.

Data analyses

Reported use and chemical components of some plants are presented in Tables 5 and 6. A total of 44 plants are presented in Table 6 with members of the family, Compositae mostly reported. Compositae (asteraceae) is the

Table 5 Chemical components and target microbial group of some medicinal plants

Botanical name	Family name	English name	Plant part	Chemical components	Target microorganism(s)	Reference
<i>Allium cepa</i>	Alliaceae	Onion	Leaves, bulb	Chrysophanol, aloe-emodin, hydroxyl-2,5-dimethylchromone, Aloin A and B, Aloesin, Aloenin B, 10-hydroxyaloin B	<i>Candida</i>	Shams-Ghahfarokhi et al. [165]
<i>Aloe barbadensis</i>	Aloeaceae	Burn plant, <i>Aloe vera</i> , medicinal aloe	Leaves	Barbaloin, chrysophanol glycoside, aglycone, aloe-emodin, aloesone, aloesin	<i>Corynebacterium</i> , <i>Salmonella</i> , <i>Streptococcus</i>	Athiban et al. [166]
<i>Cassia angustifolia</i>	Caesalpiniaceae	Senna	Pods, fruit, stems, leaves	Oxymethylantraquinone, flavanols, isorhamnetin, Kaempferol, rhein, emodin, sennosides, aloe-emodin, emodin glucoside	<i>Staphylococcus aureus</i>	Singanboina et al. [167]
<i>Glycyrrhiza glabra</i>	Papilionaceae	Mulaithi	Root	Glycyrrhizin, glycyrrhetic acid, isoliquiritin, isoflavones	<i>Staphylococcus aureus</i> , <i>Mycobacterium tuberculosis</i>	Varsha et al. [168]
<i>Lawsonia inermis</i>	Lythraceae	Heena	Leaves, seeds	Lawsonic acid, 2-hydroxy-1, 4-naphthoquinone resin, tannin, gallic acid, saponin, trimethylamine, sterols	<i>Staphylococcus aureus</i>	Habbal et al. [169]
<i>Panax notoginseng</i>	Araliaceae	Chinese ginseng, notoginseng	Root	Saponin, flavonoids, polyacetylenes, peptides, ginsenosides, polysaccharides	<i>Escherichia coli</i> , <i>Sporothrix schenckii</i> , <i>Trichophyton</i>	Wang et al. [170]
<i>Rabdosia trichocarpa</i>	Lamiaceae	Dong ling cao	Leaves	Sodoponin, ponidicin, oridonin, odonicin, lasiodonin, lasiokaurinol, rubescensin C, rabdosin A, Ememogin	<i>Helicobacter pylori</i>	Kadota et al. [171]
<i>Rumex crispus</i>	Polygonaceae	Curly dock, yellow dock	All parts although the root is the most active	Beta-sitosterol, hexadecanoic acid, chrysophanol, physcion, emodin, catechin	<i>Escherichia coli</i> , <i>Salmonella</i> , <i>Staphylococcus</i>	Wegiera et al. [172]
<i>Santolina chamaecyparissus</i>	Asteraceae	Cotton lavender	Leaves, flowers	Artemisinin ketone, dihydroaromadendrene, β -phellandrene	Gram positive bacteria, <i>Candida</i>	Salah-Fatnassi et al. [173]
<i>Taraxacum officinale</i>	Asteraceae	Dandelion	Leaves	Phytosterols, sesquiterpene lactones, flavonoids, amentin, quercetin, luteolin	<i>Streptomyces cerevisiae</i> , <i>Candida albicans</i>	Liang et al. [174]

Table 6 Reported uses of some plants

Botanical Name	Family	Plant part used	Target Antimicrobial action	References
<i>Acacia nilotica</i>	Leguminosae – Mimosoideae	Whole plant	Water treatment	[30]
<i>Acacia seyal</i>	Leguminosae – Mimosoideae	Whole plant	Water treatment	[30]
<i>Acacia tortilis</i>	Leguminosae – Mimosoideae	Whole plant	Water treatment	[30]
<i>Acacia etbaica</i>	Leguminosae – Mimosoideae	Whole plant	Water treatment	[30]
<i>Abizia anthelmintica</i>	Leguminosae – Mimosoideae	Whole plant	Water treatment	[30]
<i>Euclea divinorum</i>	Ebenaceae	Whole plant	Water treatment	[30]
<i>Plumbago zeylanica</i>	Plumbaginaceae	Whole plant	Water treatment	[30]
<i>Moringa oleifera</i>	Moringaceae	Seeds	Water treatment	[31]
<i>Jatropha carcus</i>	Euphorbiaceae	Seeds	Water treatment	[31]
<i>Guar gum</i>	Fabaceae	Seeds	Water treatment	[31]
<i>Moringa oleifera</i>	Moringaceae	Seeds	Water treatment	[60]
<i>Jatropha carcus</i>	Euphorbiaceae	Seeds	Water treatment	[60]
<i>Guar gum</i>	Fabaceae	Seeds	Water treatment	[60]
<i>Achillea millefolium</i>	Compositae	Whole plant	Antimicrobial	[175]
<i>Allium cepa</i>	Alliaceae	Bulb	Antimicrobial	[176]
<i>Allium sativum</i>	Alliaceae	Bulb	Antimicrobial	[177]
<i>Anemone pulsatilla</i>	Ranunculaceae	Whole plant	Antimicrobial	[178]
<i>Ranunculus bulbosus</i>	Ranunculaceae	Whole plant	Antimicrobial	[178]
<i>Anethum graveolens</i>	Umbelliferae	Seed	Antimicrobial	[179]
<i>Artemisia dracuncululus</i>	Compositae	Leaves	Antimicrobial	[180]
<i>Moringa oleifera</i>	Moringaceae	Seeds	Water treatment	[181]
<i>Luffa cylindrica</i>	Cucurbitaceae	Seeds and fruit	Water treatment	[182]
<i>Moringa oleifera</i>	Moringaceae	Seeds and leaves	Water treatment	[183]
<i>Berberis vulgaris</i>	Berberidaceae	All parts (mostly root)	Antimicrobial	[184]
<i>Calendula officinalis</i>	Compositae	All parts (mostly leaves)	Antimicrobial	[185]
<i>Camellia sinensis</i>	Theaceae	Leaves	Antimicrobial	[186]
<i>Cannabis sativa</i>	Cannabidaceae	Leaves, resin	Antimicrobial	[187]
<i>Capsicum annum</i>	Solanaceae	Fruit	Antimicrobial	[188]
<i>Carum carvi</i>	Umbelliferae	Seed	Antimicrobial	[189]
<i>Citrus sinensis</i>	Rutaceae	Fruit	Antimicrobial	[190]
<i>Coriandrum sativum</i>	Umbelliferae	Seed	Antimicrobial	[191]
<i>Eucalyptus globules</i>	Myrtaceae	Leaves	Antimicrobial	[192]
<i>Humulus lupulus</i>	Cannabidaceae	Fruit	Antimicrobial	[193]
<i>Hydrastis Canadensis</i>	Ranunculaceae	Whole plant	Antimicrobial	[194]
<i>Hyssopus officinalis</i>	Labiatae	Leaves	Antimicrobial	[195]
<i>Laurus nobilis</i>	Lauraceae	Leaves	Antimicrobial	[196]
<i>Malus sylvestris</i>	Rosaceae	Fruit, leaves, bark	Antimicrobial	[197]
<i>Matricaria chamomilla</i>	Compositae	Flowers	Antimicrobial	[198]
<i>Melissa officinalis</i>	Labiatae	Leaves, flowers	Antimicrobial	[199]
<i>Peganum harmala</i>	Zygophyllaceae	Fruit, seed	Antimicrobial	[200]
<i>Solanum tuberosum</i>	Solanaceae	Tuber	Antimicrobial	[201]
<i>Thymus vulgaris</i>	Labiatae	All part	Antimicrobial	[202]
<i>Tussilago farfara</i>	Compositae	All part	Antimicrobial	[203]
<i>Vicia faba</i>	Leguminosae	Seed pod	Antimicrobial	[204]

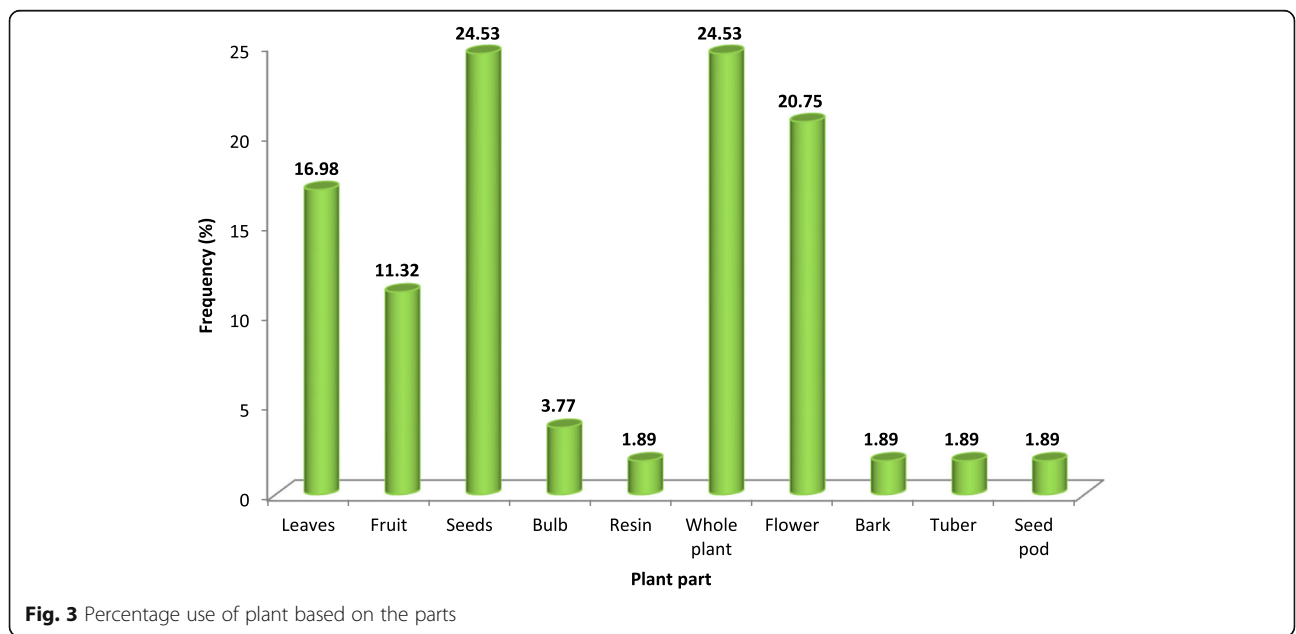
most diverse family of angiosperms and has a worldwide distribution. The family has been reported for its enormous importance in popular medicine and is the major plant studied for use in many ethno-medicinal researches [160–162]. The family Compositae is nested high in the Angiosperm phylum. The family contains the largest number of described, accepted species of any plant family [163]. The diverse application of Compositae has been attributed to the wide array of bioactive component they contain as well as the higher likeliness of the people to experiment with members of this family. Conversely, the survey by Lawal et al. [164] reveals the family Leguminosae as the mostly used family and that compositae was barely used. However, *Ageratum conyzoides* and *Vernonia amygdalina*, both of which belong to the family Compositae were reported as commonly used species ethno-medicinally.

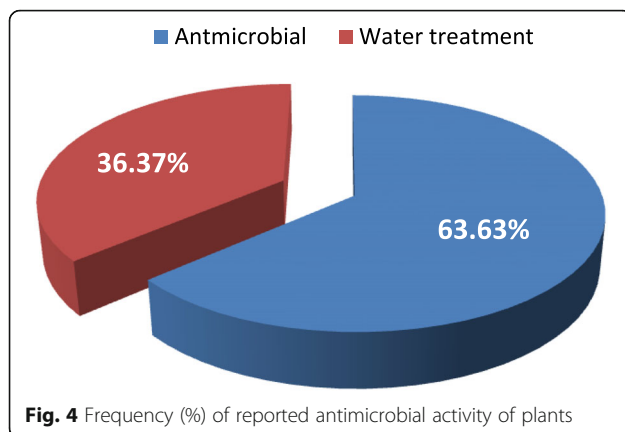
During the survey, it was apparent that whole plants and seeds (24.53%) are mostly used. Since individual plant parts have been reported for effective activity, the whole plant biomass is assumed to possess better activity and may account for the high value of whole plant material use as compared to other plant parts. The use of whole plants is usually not preferred since the removal of whole plant threatens conservation of plant species. The seeds (24.53%), flowers (20.75), leaves (16.98%) and fruit (11.32%) are therefore preferable as observed in Fig. 3 as against bulb (3.77%), resin (1.89%), bark (1.89%) and tuber (1.89%). This result does not align with the findings of Ozioma et al. [205] who reported leaves to possess more effective properties than other parts. As established by Ullah et al. [206], leaves are more reportedly used and followed by fruit (15%) among plant parts

used during an indigenous study. Leaves, roots and bulbs are the most desirable parts because they contain a high concentration of bioactive compounds. Compared with the whole plant and roots, the use of leaves or arial part of plant is much better for sustainability of natural plant products and biotechnology [207]. The use of plant products in water treatment needs to gain more research attention as they can be effective alternatives for conventional agents of water disinfection. The observation in Fig. 4 suggests that novel applications of plant products need to be explored further since more antimicrobial activities (63.63%) exist for plant materials than water treatment application (36.37%). *Moringa* seeds have been greatly studied for water treatment due to the presence of cationic proteins (dimeric) responsible for their anti-coagulant potential [208, 209]. *Moringa oleifera* extracts as well as other natural coagulants are presently in demand because they are less toxic and ecofriendly [183]. Reports have also shown that combined treatment can present better coagulation effect as seen in Alam et al. [183] report. There is always a need to carry out test to ascertain the toxicity of plants extracts to be used in water treatment and ensure its effect falls within the WHO guideline values, to be proved effective [60].

Current challenges

There are current issues which call for caution during herbal and plant products usage. Safe plants and those with positive health effects must be identified prior to use and product formulation in water disinfection. Regulations in herbal remedies and isolation of pure and safe compounds rather than crude usage may be necessary





during the considerations of plant products. Herbal remedies can be risky to human health [210] when inappropriately used. Inappropriate combination with synthetic biocides may act to reduce the potency of conventional products. Risks may exist and be triggered by age, genetics and concurrent use of other drugs [211] for products involving plant materials. Alkaloids and cardiac glycosides have been reported for adverse effects. Some herbs with adverse effects are described by Reid et al. [212], Allard et al. [213], Maffe et al. [214], and Fatima and Nayeem [215]. Some plants previously reported in literature for adverse effects include *Allium sativum*, *Panax ginseng*, *Silybam marianum*, *Vitis vinifera*, *Aloe barbadensis*, *Valeriana officinalis* and *Salix daphnoides*, [210, 216–218]. Leaves of *Ginkgo biloba* have been reported for allergic skin reaction and seizures [210]. Chemical complexity of some plant extracts, lack of standardisation, slow working rate, poor water solubility, extraction and purification complexities are limitations that need to be overcome for industrial adoption of phytochemicals in water treatment.

Conclusion and key report findings

This review aimed at establishing emerging applications of phyto-biotics in water treatment and associated challenges in combating multidrug resistant organism in water disinfection. It has been established that plant-derived compounds are environmentally friendly, usually less toxic and have a broad medicinal application. These plant products are generally widespread, affordable, and have significant antimicrobial efficacy. Secondary metabolites from plants have found great usefulness against resistant microorganisms and extracts of plants have been used in water treatment as natural coagulants and in reduction of microbial count of water borne pathogens. A major observation is that plant materials possess multifaceted components with manifold actions and capabilities in different fields; a characteristic not commonly found in synthetic counterpart. Challenges impeding progress

and development of plants as useful biotechnological products, therefore beckon for attention to aid wide applications of phytobiotics. The use of phytochemicals in combination with synthetic antimicrobials as adjuvant needs a boost as this is a current problematic area. Novel investigations in the field of phytobiotics should engage modern methodologies such as proteomics, genomics, and metabolomics to screen safe herbs and isolate pure compounds in order to minimise challenges confronting phytobiotic safety and standardisation.

Abbreviations

MR: Microbial resistance; HIV 1: Human immunodeficiency virus 1; DNA: Deoxyribonucleic acid

Acknowledgements

Nil

Authors' contributions

All authors listed have significantly contributed to the development and the writing of this article. A.O.A conceptualised and developed the manuscript; M.A.A assisted in statistical analysis and arrangement of data; J.N.E, T.A.M.M and J.O.O read, corrected and improved the general output of this work. The author(s) read and approved the final manuscript.

Funding

There has been no significant financial support for this work that could have influenced its outcome.

Availability of data and materials

The content of this work is original and all ethical issues were well considered during the manuscript development.

Ethics approval and consent to participate

This research involves no use of experimental animals or human and need for ethical approval.

Consent for publication

All authors agreed to publish this work after a thorough peer review by *Clinical Phytoscience Journal*.

Competing interests

The authors declare that they have no competing interests.

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Received: 26 March 2020 Accepted: 2 February 2021

Published online: 24 March 2021

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