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Chemical Composition, Pharmacological Activities, and Biofuel Production of *Eichhornia crassipes* (Water Hyacinth): A Review

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Abstract: *Eichhornia crassipes* (Mart.) Solms, commonly known as water hyacinth, is one of the free-floating macrophytes with substantial damaging effects on aquatic environment, but it has significant industrial and medicinal applications. Several metabolites such as vitamins, tannins, saponins, terpenoids, phenolic compounds, lignins, flavonoids, alkaloids, and sterols have been reported from the plant. The presence of such secondary metabolites made it possess a wide array of therapeutic properties, of which alkaloids, phenolic compounds, triterpenoids, flavonoids, tannins, and saponins reported from the plant were found to show promising pharmacological effects. This review endeavors to provide a comprehensive and up-to-date compilation of documented chemical constituents, pharmacological activities, and renewable energy profiles of water hyacinth. The literature encountered showed that potassium, chlorine, calcium, and aluminum were among the nutritionally important elements reported in large amounts from the plant. In this review, the findings of different extracts (methanol, aqueous, chloroform, and hexane extracts) of the plant have been reviewed for their pharmacological and biological effects and results were promising. The plant's anti-inflammatory, antioxidant, antifungal, antiaging, anticancer, hepatoprotective, and antibacterial properties, as well as other biological activities like insecticidal, allelopathic, and larvicidal effects, are extensively documented. The plant also demonstrated a wide spectrum of uses, including biofuel production, compost production, and bioremediation. On the other hand, clogging of waterways, breeding grounds for pests and disease, reduction of water quality, loss of biodiversity, and economic recession in invaded areas are negative aspects associated with it. So, the present review summarizes the potential of *Eichhornia crassipes* as a valuable source of natural compounds with desirable pharmacological effectiveness, predicting that the compilation will benefit future studies. The renewable energy profiles of the weed are also well presented.

Keywords: Biofuel, *Eichhornia crassipes,* Pharmacological activities, Renewable energy.

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INTRODUCTION

Natural resources, especially plants, have long been used as the basis of traditional and modern medicine systems. Such widespread dependence of human beings on natural resources has raised marvelous attention in the scientific world (1), which eventually led to the isolation of an enormous number of phytochemicals with significant multipurpose advantages (2). Marine plants have a large number of social, traditional, economic, and environmental benefits. Some aquatic plants are used in human diet, whereas others have medicinal values and are sources of vitamins, minerals, and renewable energy (3). Aquatic herbs and weeds are known to differ widely in their physico-chemical constituents as a result of the genotype of the plant species, seasonal variation, and location. Hence, an insight into their phytochemistry is important if utilization prospects are to be considered (4).

Eichhornia crassipes, also known as water hyacinth (Figure 1), is an aquatic plant belonging to the family *Pontideraceae* native to South America (5, 6).

The plant is considered as one of the most invasive weeds due to its rapid spread, ecological adaptability, and negative impacts on the environment (7-11), economic development, and human health (12, 13). It can rapidly grow to very high densities (over 60 kg/m^2), completely clogging water bodies, which in turn may have negative effects. The plant thrives in tropical deserts, subtropical or warm temperate deserts, and rainforest zones (14). It tolerates annual temperatures ranging from 21.1°C to 27.2°C and its pH tolerance is estimated at 5.0 to 7.5. Water hyacinth is also called "the beautiful blue devil", known by its lavender flowers, short stems and shining bright leaves which spreads at an alarming rate in aquatic grounds. The plant is able to tolerate both fresh and seawater and thus its spread has no boundaries (15).

E. crassipes has harmful side effects on human health, aquatic environment, and economic aspects of water bodies (16, 17). The extensive impacts of the plant falls to its quick growth in large areas of aquatic environment and is able to destroy the quality and quantity of waterbodies (18-20). Thus, it can create higher sedimentation rates within the plant's complex root structure and increase evapotranspiration rates from water hyacinth leaves when compared to open water, even by a factor of 10 and cause scarcity of water in some areas. Dense mats of the weed also decrease the dissolved oxygen concentrations, thus creating good breeding conditions for mosquito vectors of malaria, encephalitis, and filariasis beneath these mats (21).

The plant reduces the yield of phytoplankton and submerged vegetation under dense mats. It also destroys the native vegetation and associated flora, thus causing a disproportion in marine environment (22). The large mass of the plant in water bodies also affects the lives of fish and other aquatic communities. Recent reports of huge invasions and their environmental problems have been revealed from different parts of the world, like Lake Tana of Ethiopia, Lake Victoria of Uganda, other regions of East Africa, Lake Chapala of Mexico, Lake Navishka of Kafue river, Zambia, and Florida (12, 21).

A number of traditional and mechanical weed management approaches are applied to control the fast spread of the weed (23). Chemical and biological control methods are being used to control it but such methods may lead to water pollution and other aquatic life problems (5). Recently, much emphasis has been placed on harvesting this aquatic plant for practical purposes in order to partially offset the cost of removing plants from waterways and using them as an economical source in many parts of the world (21). Thus, the present review endeavors to provide a comprehensive and up-to-date compilation of documented chemical constituents, pharmacological activities, and renewable energy profile of water hyacinth and discusses future potentials and threats of the weed.

Figure 1: *Eichhornia crassipes* (24).

CHEMICAL COMPOSITION, PHARMACOLOGICAL ACTIVITY AND BIOFUEL POTENTIAL OF *Eichhornia crassipes*

Chemical Composition of *Eichhornia crassipes*

The plant is rich in several secondary metabolites, including alkaloids, terpenoids, phenolic compounds, flavonoids, and tannins (25-27) (Table 3). Reports from different parts of the plant revealed that it is composed of many nutritionally important elements, of which silicon, potassium, and aluminum were reported to be in large amounts in the roots, whereas stems and leaves of the plant are rich sources of potassium, chlorine, and calcium (Table 1). Heavy metals were not found in the studied samples, and the high concentration of inorganic substances makes this plant attractive for use as compost (28).

Table 1: Elemental analysis of *E. crassipes* using energy dispersive X-ray spectroscopy (EDS), where, (mg/gdw=milligram/gram dry weight) (28).

No.	Elements (mg/gdw)	Plant part		
		Roots	**Stems**	**Leaves**
1	Sodium	0.67 ± 0.06	4.43 ± 0.60	1.51 ± 0.33
2	Magnesium	0.46 ± 0.05	5.33 ± 0.02	3.76 ± 0.59
3	Aluminum	8.84 ± 0.53	0.82 ± 0.07	0.03 ± 0.01
4	Silicon	62.80 ± 0.06	8.06 ± 0.03	2.21 ± 0.03
5	Phosphorus	1.81 ± 0.01	5.12 ± 0.06	8.61 ± 0.04
6	Sulfur	1.07 ± 0.09	2.44 ± 0.03	2.76 ± 0.02
7	Chlorine	0.71 ± 0.01	19.43 ± 0.33	17.44 ± 0.12
8	Potassium	10.92 ± 0.03	38.36 ± 0.03	47.29 ± 0.30
9	Calcium	5.30 ± 0.00	15.05 ± 0.05	16.11 ± 0.08
10	Manganese	1.96 ± 0.03	0.70 ± 0.06	0.28 ± 0.02
11	Iron	5.45 ± 0.07	0.26 ± 0.01	Not detected

The energy dispersive X-ray spectroscopy method displayed that silicon showed maximum content in the roots and potassium concentration was found to be high in the leaves and stems of the plant (Table 1) (28).

Alkali solution extracts have low molecular weight carbohydrates consisting mainly of hemicellulose and degraded cellulose, and this treatment can influence the natural durability of lignocellulosic materials (23). Moreover, the alkali solubility values of the plant are larger than the other parameters in the three sections, so the plant could be easily attacked by microorganisms (Table 2) (28).

Table 2: Physicochemical characterization of *E. crassipes* (23, 28).

No.	Parameter	Plant part		
		Roots	**Stems**	**Leaves**
1	pH	4.6 ± 0.01	4.7 ± 0.04	4.7 ± 0.14
2	Ash (wt %)	26.0 ± 0.22	26.8 ± 0.39	19.9 ± 0.25
3	Alkali solubility (wt %)	54.4 ± 0.21	52.4 ± 0.34	51.8 ± 0.27
4	Total extractives (wt %)	35.9 ± 0.82	58.0 ± 0.78	47.5 ± 0.12
5	Holocellulose (wt %)	23.7 ± 0.45	11.4 ± 0.50	17.1 ± 0.06
6	Cellulose (wt %)	16.0 ± 0.77	8.4 ± 0.21	8.7 ± 0.76
7	Hemicellulose (wt %)	7.7	3.0	8.4

The physicochemical analysis of the plant showed highest extractive values (58%) in the stem parts of *E. crassipes*. Whereas, highest alkali solubility values (54, 52, and 51%) were presented from the root, stem, and leaf parts of the plant respectively (28) (Table 2).

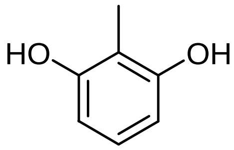
Phenolic compounds were identified from the various parts of the plant using different solvent systems (29, 30). 2-methylresorcinol **(1)**, catechol **(2)**, 4-methylresorcinol **(3)**, p-hydroxybenzoic acid **(4)**, vanillic acid **(5)** and salicylic acid have been detected in the ethanolic root extract (26, 31), whereas 4-methylresorcinol **(3)**, 2-methylresorcinol **(1)**, resorcinol and catechol **(2)**, were present in rhizomes. In a related study, an antifungal 2,5-dimethoxy-4-phenyl-benzoindenone **(6)**, a red oily metabolite, was also reported from the plant (32) (Figure 2).

Flavonoids such as Apigenin **(7)**, gossypetin **(8)**, and chrysoeiol **(9)** were also reported in petroleum and aqueous extracts (26), whereas kaempferol **(10)**, quercetin **(11)**, and isovitexin **(12)** were reported in the shoot and rhizome (15). In a related study, anthocyanins **(13)** were present in the aqueous extract of the plant (15, 26, 33, 34) (Figure 5). Moreover, gallic acid **(14)**, 3,4-dihydro-2-phenyl-2H-chromen-3-ol **(15)**, catechin **(16)**, and epicatechin **(17)** were the reported tannins in methanol and aqueous extracts (15, 35) (Figure 2).

Qualitative investigation of alkaloids by TLC showed that cytosine **(18)**, codeine **(19)**, nicotine **(20)** and quinine **(21)** are some noticeable alkaloids reported from various parts of thep lant (15, 26). A related study revealed that, β-carotene **(22)** and phytol **(23)** were also some of the terpenoids isolated from the ethanolic extracts of the plant by GC-MS. The phytochemical analysis of the methanolic extract of the plant also showed the presence of alkaloid derivatives (16). According to the report (18, 19-secoyohimban-19-oic acid, 16, 17, 20, 21-tetradehydro-16-(hydroxymethyl)-, methyl ester (15 beta, 16 E) (**24**), di amino-di nitro-Methyl dioctyl phthalate (**25**) and 9-(2,2-Dimethyl propanoilhydrazono)-2,7-bis-[2-{diethylamino)-ethoxy] dichloride (**26**) were present in the plant extracts (16, 36-38) (Figure 2).

Jayanthi *et al.*, (2011) (26) and Lalitha *et al.*, (2012) (31) reported the presence of phenalenone and sterols in various extracts of *E. crassipes* (39-43), including 4α-methyl-5α-ergosta-7,24(28)-diene-3β,4β-diol (**27**), 4α-methyl-5α-ergosta-8,24(28)-diene-3β,4β-diol (**28**), 4α-methyl-5α-ergosta-8,14,24(28)-triene-3β,4β-diol (**29**), 6α-hydroxystigmata-4,22-diene-3-one (**30**), and phenalenone derivatives (**31-35)** (31)**.**

Terpene derivatives were also presented from the methanolic extract of *E. crassipes (39, 44-46). 1,2-* Benzene dicarboxylic acid, mono-(2-ethylhexyl ester) (**36**), 1, 2-benzenedicarboxylic acid, diisooctyl ester (**37**), 1, 2-Benzenedicarboxylic acid, dioctyl ester (**38**) and Isooctyl phthalate (**39**) were among the reported terpenoid derivatives in the plant (16) (Figure 2).



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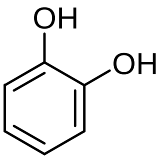

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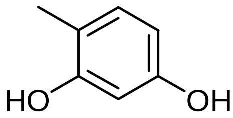

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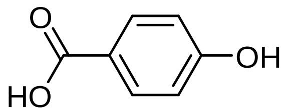

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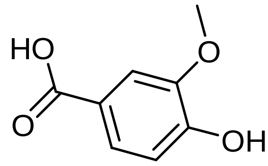

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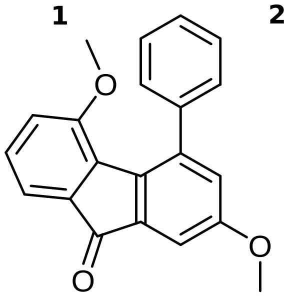

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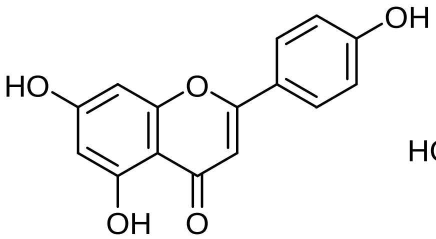

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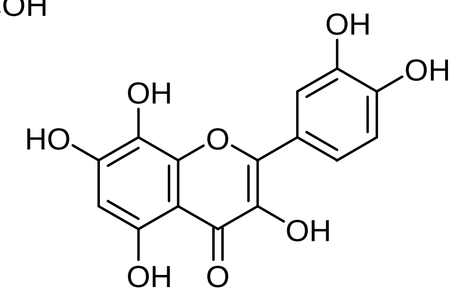

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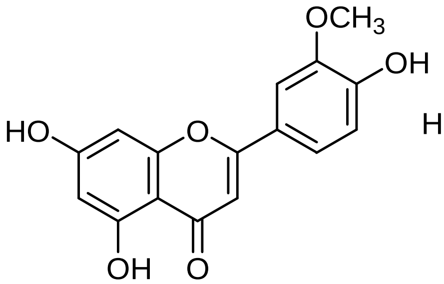

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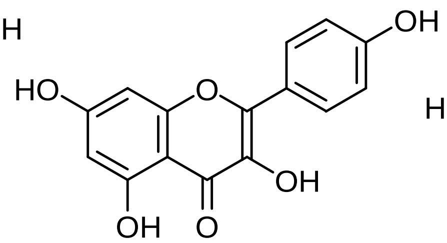

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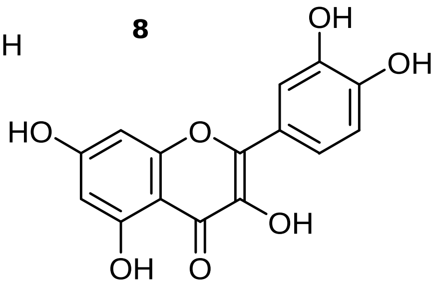

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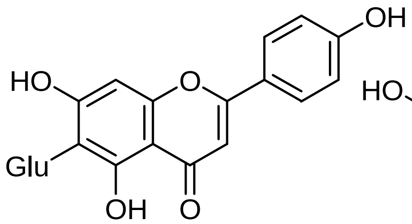

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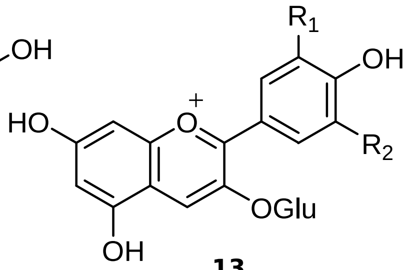

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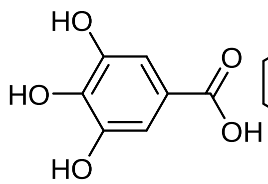

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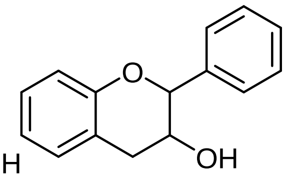

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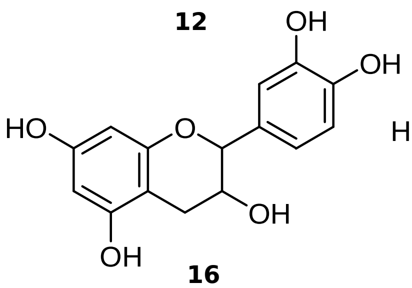

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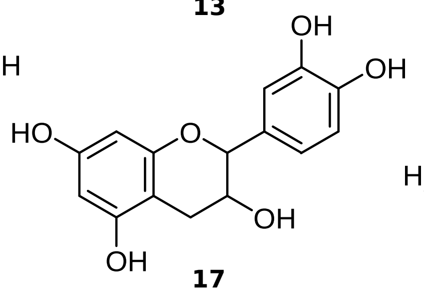

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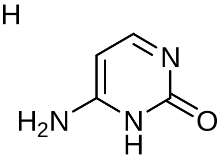

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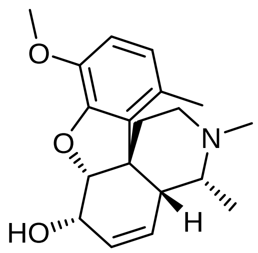

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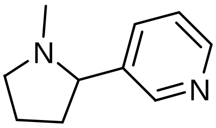

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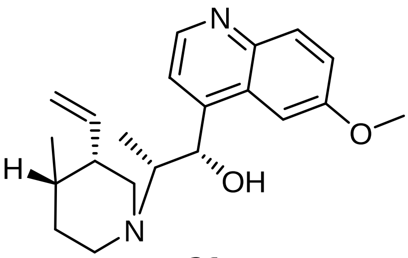

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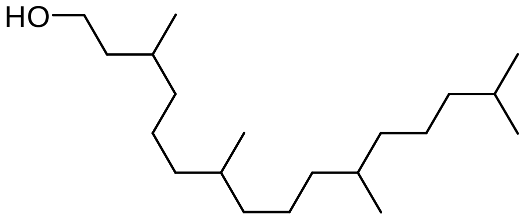

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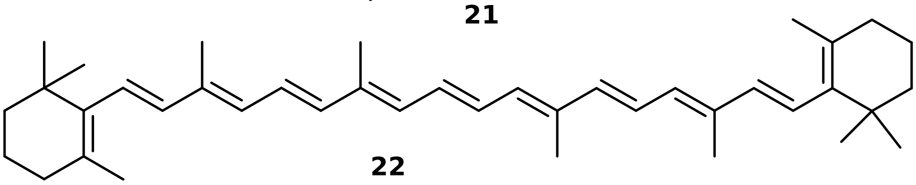

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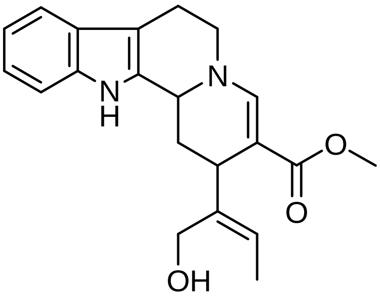

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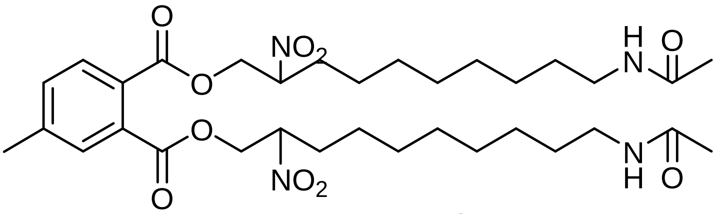

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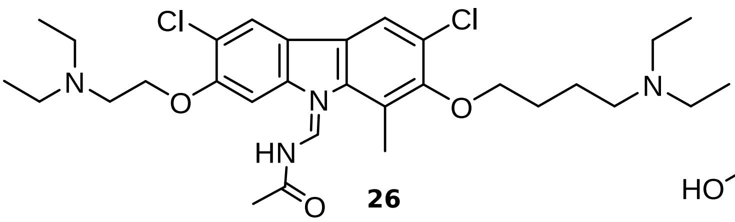

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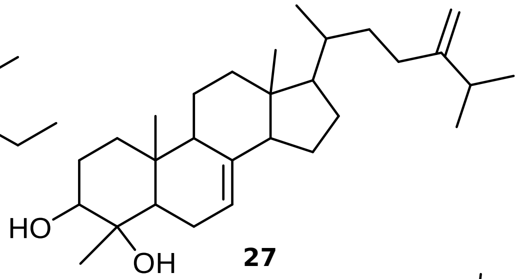

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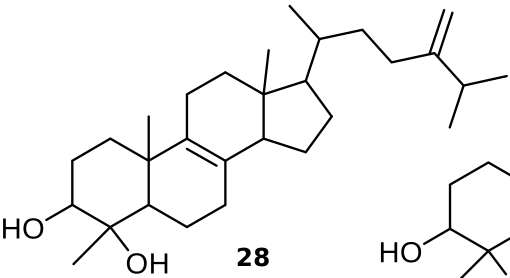

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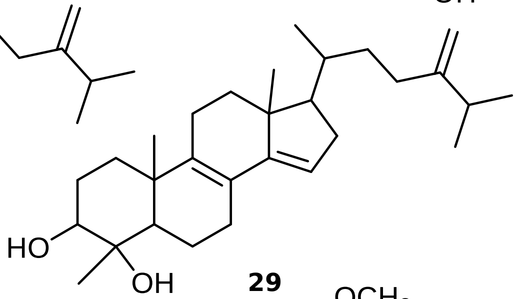

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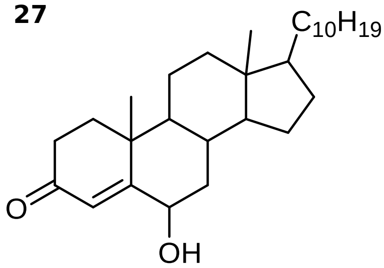

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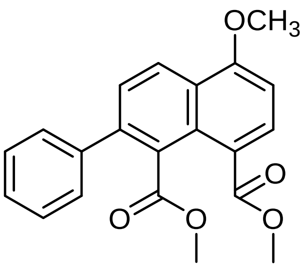

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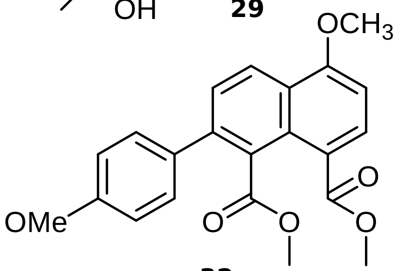

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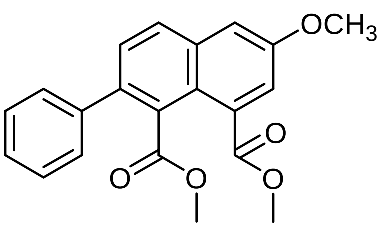

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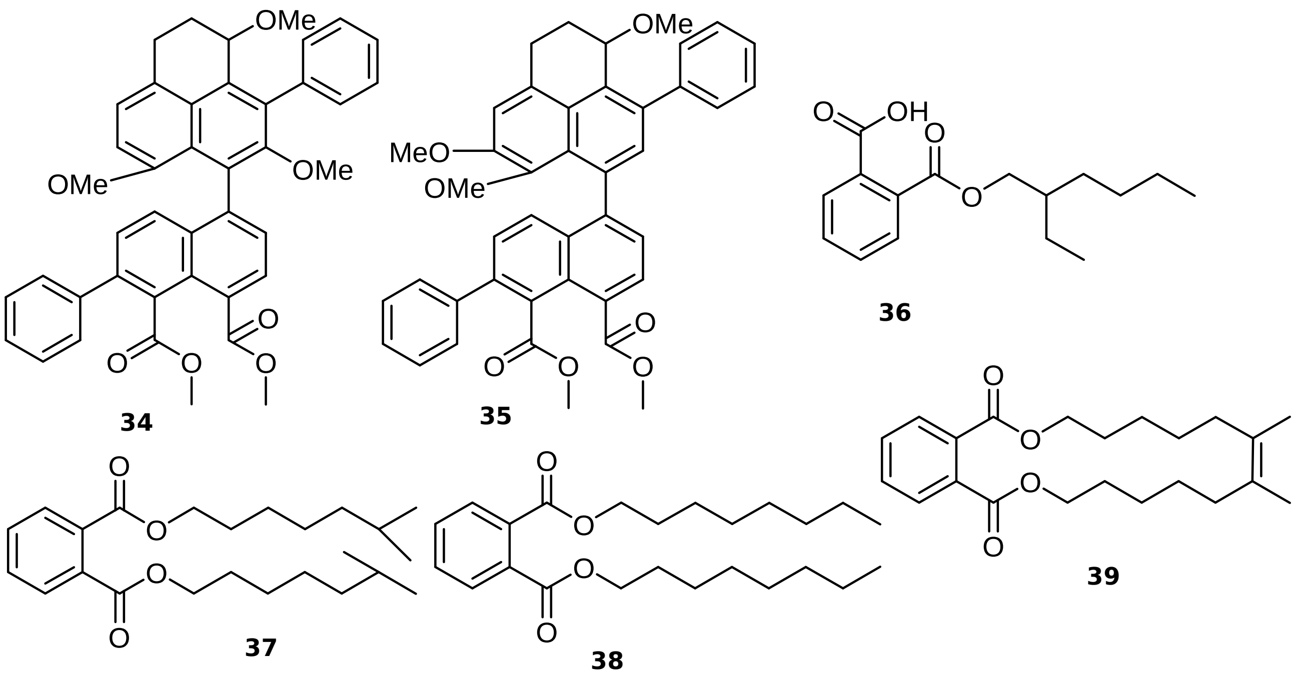

Figure 2: Suggested structures of natural products reported from *E. crassipes.*

Resins, anthraquinones, saponins, fatty acids, phenalenes, organic acids, phlobatannins, carbohydrates, proteins, and lipids were also important metabolites that have been identified in the different parts of *E. crassipes* by different analytical methods (26, 47-50) (Table 3).

Table 3: Phytochemical study of leaf extracts of *E. crassipes* (26).

No.	Phytochemicals	Plant extract			
		Water	**Acetone**	**Ethanol**	**Methanol**
1	Terpenoids	+	+	+	+
2	Tannins	-	+	-	+
3	Amino acids	-	-	+	-
4	Proteins	-	-	+	-
5	Carbohydrates	+	-	+	-
6	Phenolics	-	-	+	+
7	Flavonoids	-	-	-	+
8	Alkaloids	+	+	-	+
9	Saponins	-	-	+	+

+=indicates being present and - = indicates being absent.

GC-MS results of the extracts of the plant displayed twenty organic acids, three steroids, and one terpenoid (39). Carboxylic acids were reported in the leaf and stem extracts. Levulinic acid, oxalic acid, caprilic acid, malonic acid, nonanoic acid, succinic acid, myristic acid, lauric acid, linolenic acid, palmitic acid, oleic acid, pentadecanoic acid, vaccenic acid, linoleic acid, arachidonic acid, squalene, cholestane, β-stigmasterol, and spirostane were among the reported compounds in the extracts of the plant using different solvent systems (30, 39, 44, 45, 51).

Another report, Verma *et al.*, (2021) (52), showed that GC-MS analysis of the extracts of *E. crassipes* displayed the presence of various components in the methanol leaf extracts of the plant. Palmitic acid (24.18%), 9-hexadecenal (10.29%), neophytediene (8.42%), 3-undecanone (7.36%), stearic acid (6.35%), and vitamin E (5.85%) were among the major compounds reported in the study.

Pharmacological Activities of *Eichhornia crassipes*

Antibacterial, antifungal, antioxidant, anti-inflammatory, immunomodulatory, and cytotoxicity effects of *E. crassipes* were broadly studied and results showed that the plant possess promising pharmacological activities (53-56) (Table 4).

Table 4: Selected pharmacological activities of *E. crassipes.*

Plant part studied	Extract type	Type of study/ Tested cell/ Animal used	Results	Refs
		Antioxidant activities		
Leaf	Ethanol	*In vitro* (DPPH)	A good antioxidant activity was observed	(57)
The whole parts	n-hexane, methanol, chloroform	DPPH	The IC50 values were 0.387, 0.018 and 1.03 µg/mL respectively	(58)
Leaf	Chloroform, ethanol	Lab assay	The extracts showed good activity at all concentrations (25-100 µg/mL)	(59)
The whole parts	Methanol	DPPH	Showed high activity between 97.0 ± 5.4 and 97.4 ± 2.7 µg/mL	(60)
		Anticancer activities		
Leaf	Ethanol	Breast cancer cell lines	80% inhibition of the cell growth at 100 µg/mL	(44)
The whole parts	Methanol	HeLa cell lines	Showed acceptable efficiency with IC_{50} of 1.6	(61)
Leaf	50% methanol	B16F1 mouse melanoma	Showed antitumor effect towards radiotherapy	(44)
		Anti-inflammatory activities		
The whole parts	Methanol	Lab assay	Showed strong activity with maximum inhibition of albumin denaturation protein (80%) at 500 µg/mL	(58)
		Antimicrobial activities		
Flowers	Methanol	*S. aureus* (disc diffusion method)	Showed significant antibacterial activity at 20 µg/mL	(62)
The whole parts	n-hexane	*P. aeruginosa, S. aureus, E.coli, Salmonella typhi* (disc diffusion method)	Tested active against all pathogens except *S.typhi*	(44)
Leaf	Hydro-methanolic extract	Human and aquatic pathogens (disc diffusion method)	Showed good antimicrobial activity against *S. iniae* and *E. coli* with MIC of 128-512 mg/mL and 64-256 mg/mL respectively	(63)
Leaf	Ethanol	Sub-gingival plaque bacteria colony (serial tube dilution method)	No growth at 12.5, 25, 50, and 100%. Growth was observed at 3.125%	(64)

Antimicrobial Activity

The plant displayed good antibacterial activity (40, 65-73) against certain Gram-positive bacteria (*Staphylococcus aureus, Streptococcus faecalis* and *Bacillus subtilis*) and Gram-negative bacteria (*Escherichia coli*). Of the results studied by Vadlapudi *et al.* (2010) (74) towards six extracts, n-butyl alcohol extract displayed promising antibacterial activity against *S. pyogenes, S. aureus,* and *E. coli* compared to streptomycin (Table 5) (74). Verma *et al.* (2021) (52) reported the antibacterial activity of ethanol and methanol extracts which showed promising inhibition against *V. harveyi* at different concentrations (5, 10, 20 mg/mL) compared to ciprofloxacin.

Various extracts of the plant failed to show antifungal activity towards *Aspergillus niger* and *Aspergillus flavus*, whereas all fractions were active against *Trichophyton megnini* (74) (Table 6). The most promising observation was the ethanol and water extracts of the plant, with good activity against *A. flavus* compared to Fluconazole (31). Substantial studies have reported that compounds isolated from the plant exhibit antibacterial properties against many gram positive and gram negative bacteria (53, 55). The reported antimicrobial activities of the weed were due to the alkaloids, saponins, and tannins screened in the plant (Table 3).

Anti-oxidant Activity

E. crassipes showed good antioxidant activity (30, 33, 58) and the glutathione content of the plant was found to be 32 ± 1.6 nmol/gram of dry water hyacinth leaves (75). The methanol extract revealed promising activity at 250 µg/mL with 80% inhibition compared to ascorbic acid at the same concentration (90% inhibition). The antioxidant potential of the extracts using different solvent systems by both DPPH and ABTS methods displayed a dose-dependent activity (60, 76).

The methanol and ethanol leaf extracts studied by Verma *et al.*, (2021) (52) showed that both extracts possess good antioxidant properties in reference to the standards, with higher activity observed for the methanol extract (52, 57) (Table 7). The antioxidant properties of the plant may be due to the presence of flavonoids and phenolic compounds in their extracts, which have excellent radical scavenging activities (Table 3).

Table 5: Antibacterial activities of *E. crassipes* (74).

No.	Bacterial pathogens	Zone of inhibition in different solvent systems (diameter in mm)						
		n-butyl alcohol	Methanol	Ethyl acetate	Ethanol	Distilled water	Acetone	Standard (Streptomycin)
1	*S. pyogenes*	12±0.23	8±0.16	10±0.35	9±0.18	-	9±0.42	19±0.50
2	*S. aureus*	10±0.14	10±0.33	-	10±0.31	-	-	12±0.20
3	*S. pullorum*	10±0.31	8±0.11	-	-	-	8±0.10	13±0.15
4	*P. vulgaris*	-	-	-	10±0.28	9±0.21	11±0.27	14±0.16
5	*E. coli*	10±0.20	9±0.22	-	9±0.32	8±0.30	10±0.16	12±0.44

Table 6: Antifungal activities of *E. crassipes* (74).

No.	Fungal pathogens	Zone of inhibition in different solvent systems (diameter in mm)						
		n-butyl alcohol	Methanol	Ethyl acetate	Ethanol	Distilled water	Acetone	Standard (Fluconazole)
1	*T.megnini*	10±0.30	-	9±0.33	8±0.22	9±0.14	10±0.22	19±0.40
2	*C. albicans*	11±0.16	-	-	8±0.24	9±0.37	10±0.23	20±0.42
3	*A. ochraceus*	10±0.26	-	-	12±0.10	9±0.28	15±0.41	18±0.10
4	*A. fumigates*	10±0.38	-	8±0.46	13±0.12	10±0.30	14±0.10	19±0.22
5	*A. flavus*	-	-	-	10±0.15	9±0.20	10±0.12	13±0.25

Table 7: Antioxidant activity of methanol extract of *E. crassipes* (52).

Treatments	Concentrations (µg/mL)	% inhibition of DPPH
Ascorbic acid	50	52
	100	69
	150	74
	200	82
	250	90
Methanol extract	50	44
	100	59
	150	65
	200	72
	250	80

According to the results presented by Aboul-Enein *et al.* (2014) (16), nine fractions (alkaloid and terpenoid derivatives) were isolated from the methanol extract of the plant and showed anticancer and antioxidant activities. The crude methanolic extract showed the highest antioxidant activity with an IC_{50} of 74.80 ± 4.5 µg/mL. Three of the nine compounds recorded comparable activities (92.40 ± 6.5, 95.4 ± 3.1, and 96.5 ± 2.7 µg/mL).

Anti-inflammatory Activity
The anti-inflammatory effects of the aqueous extract, ethyl acetate, and petroleum ether extracts of the plant were presented and results were promising (77-79). The results of the study showed a substantial reduction in the growth of oedema in the hind paws of the mice when treated with the extracts. The three solvent systems displayed variable anti-inflammatory effects. The report also revealed that the petroleum ether and ethyl acetate extracts showed maximum inhibition of the oedema (64.8% and 67.5%, respectively). The presence of phenolic compounds, flavonoids, alkaloids, and anthraquinones in the extracts of the plant plays a significant role in the anti-inflammatory activities of the plant (80) (Table 3).

A related study by Tulika *et al.* (2017) (81) on the methanol extract of the plant showed promising results. The activity was examined by the inhibition of albumin denaturation protein. The evaluation of the anti-inflammatory potential of the plant extract, the inhibition of protein denaturation was studied, and results were encouraging. According to the study, the methanol extract of the plant displayed promising inhibition of albumin denaturation at the concentration of 500 µg/mL with 79% of inhibition compared to ibuprofen (96% of inhibition) (82)(Table 8).

Table 8: Anti-inflammatory activity of methanolic extract of *E. crassipes* (83).

Treatments	Concentrations (µg/mL)	% inhibition of protein denaturation
Ibuprofen	100	42
	200	54
	300	74
	400	80
	500	96
Methanol extract	100	20
	200	42
	300	60
	400	72
	500	79

Anti-cancer Activity
Results of anticancer activities showed that methanol extracts of the plant have moderate anticancer effects (36, 80). This phenomenon has been supported by various solvent extracts tested on mice embryonic fibroblast cell lines. The methanol extracts of the various parts of the plant at different concentrations showed anti-cancer activities against HeLa cell lines with 17% growth inhibition at 200 µg/mL using MTT assay method. The growth inhibition zones and concentrations of the extracts showed smooth relationships (Table 9) (80). The major classes of phytochemicals responsible for the anticancer effects of the plant were alkaloids, saponins, polyphenols, flavonoids, tannins, triterpenes, and quinones (84) (Table 3).

Table 9: IC_{50} analysis value of *E. crassipes* extract against HeLa cells (80).

S/No	Number of subjects	Concentration (µg/mL)	Observed responses	Expected responses	Probability
1	100	0	0	37.14	0.37
2	100	50	98	57.12	0.57
3	100	100	89	75.40	0.75
4	100	200	83	95.57	0.96

Wound healing activity
Three solvent extracts of the plant (methanol, ethyl acetate, and aqueous extracts) were investigated for their wound healing potential in an excision experimental model of wounds in rats. The experiments showed a better wound contraction effect, which was considerably greater than the control (79, 81).

Larvicidal activity
Eggs and larvae of C*hironomus ramosus chaudhuri* were subjected to various concentrations of the root extracts of the plant and showed 100% efficiency

(82). According to the reports of Lalitha *et al.* (2012) (31), putative cytokinin glucoside-like activity was detected only in leaves and flowers of the plant. The cytokinin complements of the leaves and the roots were qualitatively different. Certain cytokinins supplied by the roots are metabolized in the leaves, and certain cytokinins are synthesized in the leaves themselves. Larvicidal, pupicidal, and repellent activity carried out on petroleum ether, ethyl acetate, aqueous extracts, methanol, and ethanol fractions against *Culex quinquefasciatus* also showed good activity (82, 85).

Antitumor activity

The methanolic leaf extract of *E. crassipes* (50%) at different doses (200 mg/kg body weight to 500 mg/kg body weight) showed good response against B16F10 *in vivo* melanoma tumor bearing hybrid mice models (31). In comparison to the isolated compounds, the crude extract, displayed better activity against several tumor cells. Some fractions exhibited selective anticancer activity against a liver cancer cell line, while other fractions exhibited high anticancer activity against hormone-dependent tumor types (cervix and breast cancers). The potency of the crude extract compared to its fractions has been attributed to the auto-synergistic effect of these fractions within the same extract (60).

Source of Renewable Energy

Bote *et al.* (2020) (83) presented their work on the use of *E. crassipes* compost on other green plants such as vegetables and flowering plants and its side effects. In this report, nine morphological yield parameters were studied on saplings grown with *E. crassipes* compost and compared with the untreated ones. The experiments were carried out in kitchen gardens to demonstrate how *E. crassipes* compost can be used instead of regular compost. Based on the findings, they concluded that the green plants grown with *E. crassipes* compost showed good results in terms of all the studied parameters, suggesting that the plant can be applied effectively through the vermin composting process. A fermentative system using *E. crassipes* has been reported to produce ethanol and found to be promising (Figure 3) (83).

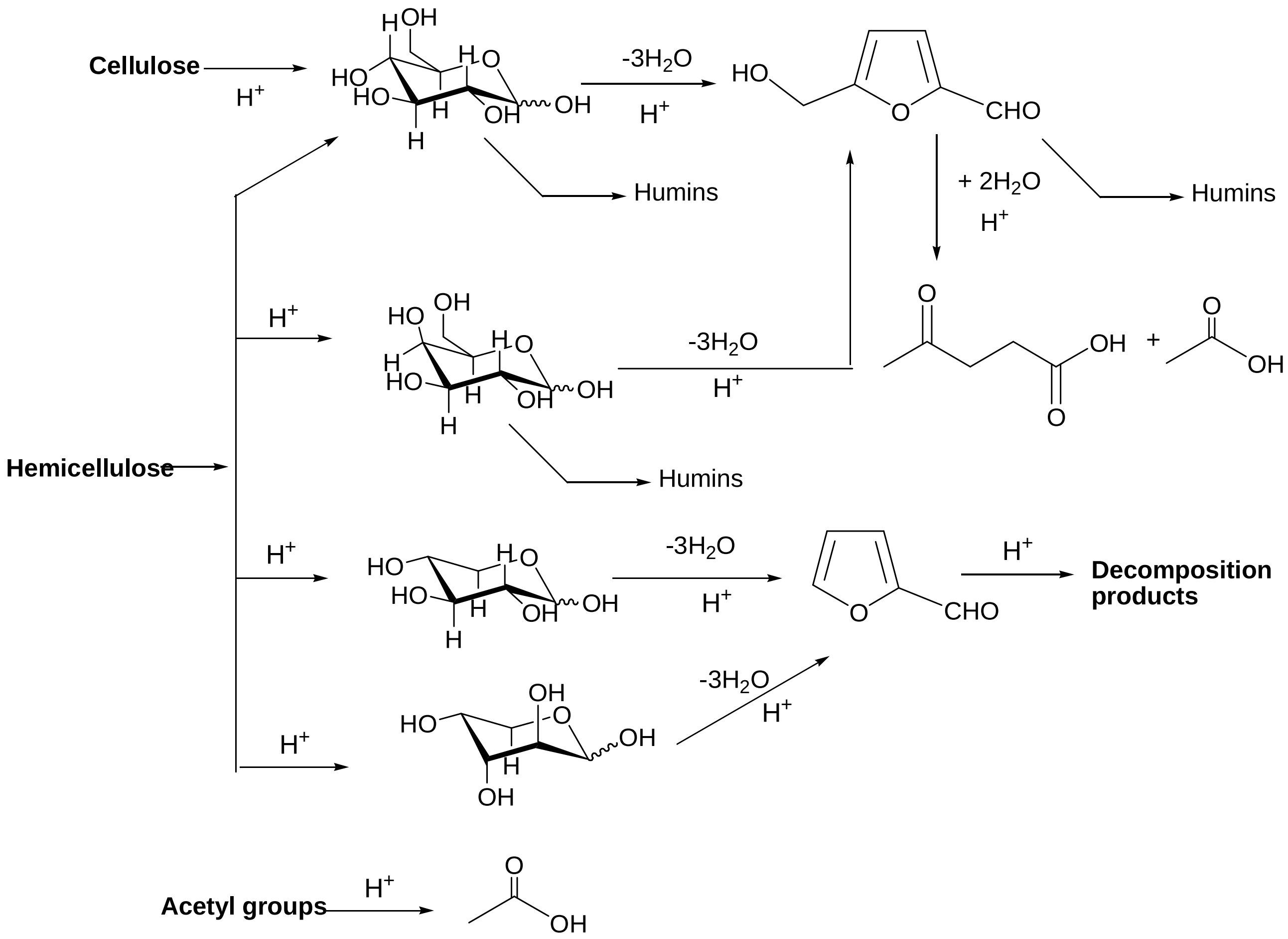

Figure 3: Hydrolysis reaction of *E. crassipes* (83).

The plant also has large amounts of lignin, cellulose, and hemicellulose, which are prominent for processing useful products such as biofuels (86-92). Recent reports revealed that *o*ne hectare of standing *E. crassipes* produces more than 70.000 m^3 of biogas. The bacterial fermentation of one ton of the plant produces about 26500 cubic foot of gas with 25.4% hydrogen, 51.6% methane, 1.2% oxygen, and 22.1% carbon dioxide (93).

Significant research has been conducted in various parts of the world to produce bio-fuel from *E. crassipes*, and the results show that the plant can be used as a future alternative source of renewable energy (94-99) (Figure 4). The plant produced biodiesel (6.36% m/m) primarily composed of saturated fatty acids. The biodiesels produced from the plant have good suitability and stability to be used in diesel engines. The by-products which are made up of glycerol and other pigments, were recorded 1.05 mmol/L and 4.69 mg/g, respectively (100).

The potential and threat of *E. crassipes* studied by Mitan (2019) (101) indicated that proper management and treatment of the plant are strongly recommended in order to utilize it as a source of energy, agriculture, water treatment, chemical and biological sources. Moreover, the proliferation of the plant needs to be more focused on maintaining the sustainability of the environment (101).

Alagu *et al.* (2019) (102) focused on *E. crassipes* biodiesel as a potential alternative fuel for existing unmodified diesel engine. The work examined the feasibility of biodiesel derived from the plant in a compression ignition engine and showed that the plant is also a potential source of renewable energy as it is available in fresh water and aquatic ecosystems in many parts of the world (102).

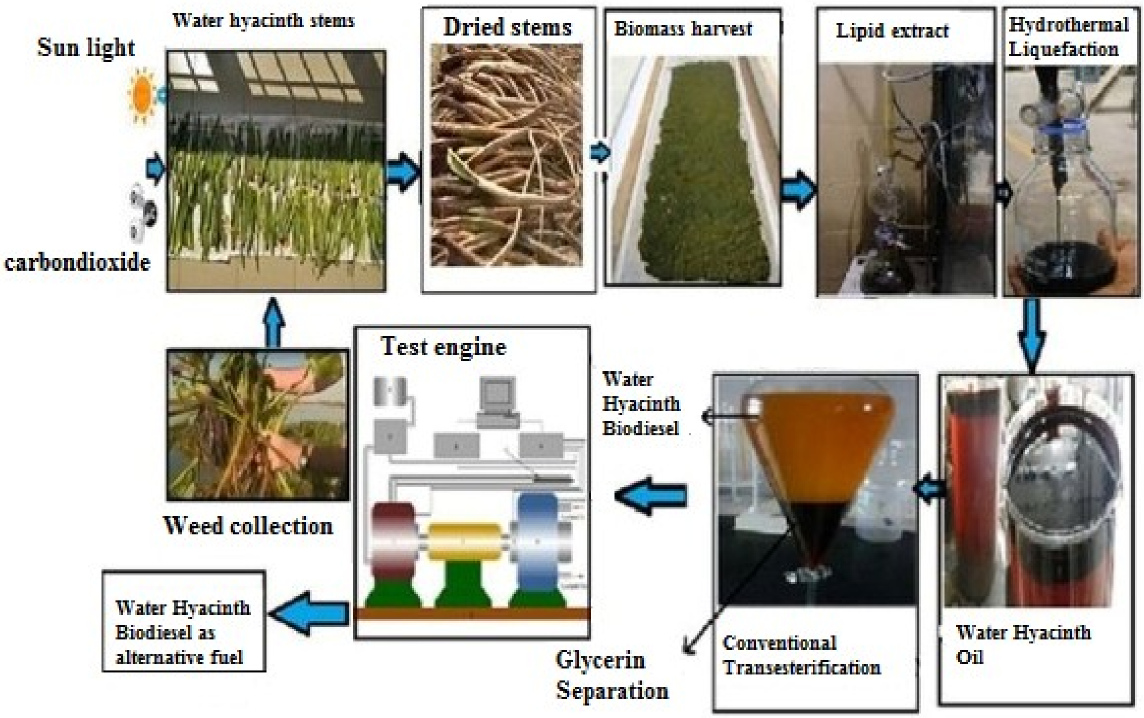

Figure 4: Schematic diagram of the experimental setup for biodiesel production.

A related study by Aswathy *et al.* (2010) (103) revealed that the plant has an excellent correlation with the standard parameters of the diesel available in the market (103) (Table 10). According to this report, water hyacinth biodiesel was mixed with petroleum diesel fuel at different volume proportions (10, 20, 30, 40, and 100%) and its properties were examined as per ASTM standards before it was used for diesel engines. The prepared test fuels were experimentally investigated in a single-cylinder diesel engine at constant speed (1500 rev/min) for their combustion, performance, and emission features. The test results showed that 20% *E. crassipes* biodiesel and 80% diesel fuel blend was equivalent to the original diesel fuel in terms of thermal efficiency and smoke emissions. Generally, the displayed heat release and cylinder pressure by *E. crassipes* biodiesel were very close to those of ordinary diesel fuel (102).

Table 10: Fuel properties of blending stocks of *E. crassipes* (102).

No.	Fuel properties	Unit	Biodiesel standard		Diesel	Water hyacinth oil	Water hyacinth biodiesel				
			ASTM D 6751	DIN EN14214			B10	B20	B30	B40	B100
1	Density at 15 °C	kg/m^3	-	860-900	838	952	841	846	858	863	887
2	Kinematic viscosity at 40 °C	mm^2/s	1.9-6	3.5-5	2.76	26.4	2.92	2.86	3.18	3.37	3.96
3	Flash point	°C	>130	>120	68	246	74	98	125	148	212
4	Pour point	°C	-	-	-20	17	-3	-4	-1	0	7
5	Cetane number	-	>47	>51	48	44	47	47.4	48.6	49.3	52.5
6	Acid value	mg KOH/g	<0.8	<0.5	-	41	0.36	0.35	0.37	0.36	0.42
7	Water content	%	<0.03	<0.05	0.02	1.8	0.03	0.03	0.02	0.03	0.04
8	Ash content	%	<0.02	<0.02	0.01	0.96	0.01	0.01	0.01	0.01	0.01

CONCLUSION AND FUTURE PERSPECTIVES

This comprehensive review was compiled to evaluate the traditional uses, chemical constituents, pharmacological activity, and biodiesel production possibility of *E. crassipes* (water hyacinth) aiming to highlight the plant's potential to develop its limited therapeutic applications in Africa, especially in Ethiopia. Different phytochemicals isolated from the plant showed anticancer, antibacterial, antifungal, and anti-inflammatory activities. Previous reports revealed that the metabolites in water hyacinth contribute to significant biological activities, especially antioxidant and antibacterial properties. In this regard, further research may be needed to explore the possibility of evaluating the plant for radical scavenging activity and possibility of developing natural antioxidants from it. The plant also displayed promising antifungal activity against *A. flavus,* and the potential of using the leaves of the plant as biofungicides should be studied further. Similarly, the potential of n-butyl alcohol extract against *S. pyogenes, S.aureus,* and *E.coli* should be considered, and further research for natural antibacterial agents should be conducted. Moreover, several patents have described the pharmacological effects of the plant, but clinical applications are still rare and need further investigation. The plant can be considered as the best alternative to cope up with the progression of regional and global environmental change as well as the depletion of fossil fuels.

The ability of this plant to invade different kinds of water bodies across different geographical zones remains a challenge. In this regard, it is recommended to conduct molecular analysis of the plant growing in different water habitats and different geographical zones with due attention to examine the similarities in the genes across the different habitats that may help to genetically modify the plant to be less invasive. In addition, considering the biodiesel efficiency of the plant in situations where controlling the growth becomes a challenge and if facilities exist to utilize the potential of this plant, efforts should be geared toward harnessing the potential of the plant as an alternative energy source i.e., biodiesel production.

CONFLICT OF INTEREST

The authors declare that they have no competing interests to disclose.

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