Phytochem Rev (2020) 19:643–658
https://doi.org/10.1007/s11101-020-09670-z

Karanja (*Milletia pinnata* (L.) Panigrahi): a tropical tree with varied applications

Abhishek Sharma · Nutan Kaushik · Himanshi Rathore

Received: 8 October 2019 / Accepted: 17 March 2020 / Published online: 9 April 2020

Abstract *Milletia pinnata*, popularly known as Karanja, is a perennial tropical tree indigenous to India, South-Eastern Asia, and Australia. This highly favored oilseed plant is used in agroforestry as well as for restoration of wastelands due to its moderate tolerance to drought and salinity. Karanja tree, though widely investigated as biofuel feedstock producer, possess wider commercializing values that can be exploited in agricultural and industrial sectors. The oil, leaves, and bark of the Karanja tree have remarkable medicinal properties. In contrast, oil cakes have broad pesticidal applications due to the presence of various bioactive constituents (e.g., karanjin and pongamol). Due to richness in proteins and fatty acids, oil cakes have also been utilized as feedstock for industrially relevant enzyme production and animal feed. In this paper, we have presented the recent and updated review of varied applications of Karanja biomass classified into medicinal, industrial, and agricultural applications.

A. Sharma · N. Kaushik (✉)
Amity Food and Agriculture Foundation, Amity University Uttar Pradesh, Noida, J-1 Block, Room No. G-18, Amity University Campus, Sector-125, Noida, Uttar Pradesh 201313, India
e-mail: kaushikn2008@gmail.com; nkaushik5@amity.edu

H. Rathore
School of Continuing Education, Indira Gandhi National Open University, New Delhi 110068, India

Keywords Biofuel · Feedstocks · Karanja · Oilseed · Applications

Introduction

Karanja (*Millettia pinnata* (L.) Panigrahi) is a promising oilseed crop that belongs to the family Fabaceae (= Leguminosae). This medium-sized tree is also known by the synonyms: *Pongamia glabra* Vent., *Derris indica* (Lam.) Bennet, and *P. pinnata* (L.) Pierre (Bala et al. 2011). It is also named 'Karum Tree' or 'Poonga Oil Tree' in English. Karanja is a glabrous, perennial tree which is probably originated in India and found in South-Eastern Asia and Australia (Sangwan et al. 2010). The tree is known to be drought resistant, nitrogen-fixing with high tolerance to salinity. It has wide adaptability to adversative climatic and soil moisture conditions and often exploited as windbreaks in tea plantations (Divakara et al. 2010). *M. pinnata* contains a dense network of lateral roots that have been known to prevent soil erosion. It is easily adapted to humid and sub-tropic regions with good drainage and sunny location. These trees can tolerate salinity and alkalinity and are commonly found along the coasts and riverbanks. In India, Karanja trees are commercially cultivated where seed ripens from February to May and are harvested during December and April (Yadav et al.

2011). *M. pinnata* is a rapidly growing medium size plant which reaches up to a height of 40 feet and spreads a broad canopy for casting shade (Sangwan et al. 2010). The plant has been reported to be grown by several methods, including direct seed sowing or by raising the seedlings in the nursery and planting or by stump cuttings. The most common and successful way is direct seed sowing, which does not require pre-treatment, and germination occurs within a period of 1 week to a month. The tree has vast economic significance due to widespread usages of its seeds, seed oils, oil cakes, flowers, fruits, barks, and roots (Fig. 1).

The oil, leaves, and bark of Karanja tree have remarkable medicinal properties while oil cakes have broad pesticidal applications due to the presence of various bioactive antinutritional constituents (e.g., flavonoids, saponins, alkaloids, triterpenes, etc.). Due to rich nutritional values, oil cakes have also been utilized as feedstock for industrially important enzyme production and animal feed (Fig. 2).

This paper aims to provide recent updates on the medicinal, agricultural, and industrial applications of Karanja tree biomass.

Medicinal applications

Karanja is an indigenous medicinal legume tree and one of the non-edible oil yielding trees with high potential for seed yield (20,000 seeds/tree) (Belide et al. 2010). For more than 80 years, all part of *M. pinnata* has been widely used as traditional medicines cross worldwide, and the responsible bioactive compound for such activities is karanjin- a furano flavonoid, which was first isolated in 1925 by Prof. Limaye.

Karanja biomass has been continuously exploited by the pharmacological companies to develop various drugs for the treatment of tumors, ulcers, and brain diseases (Muqarrabun et al. 2013; Pavithra et al. 2010). Table 1 summarizes the studies about the therapeutic properties of different plant parts of *the M. Pinnata* tree.

Antioxidant property

The physiological process in the human body leads to the production of free radicals and another group of reactive oxygen species. Such free radical leads to the destruction of cells and develop cancer, so to scavenge

Fig. 1 Botanical features of Karanja tree: roots, bark, leaves, flowers, shells, seeds, seed oil and deoiled cake

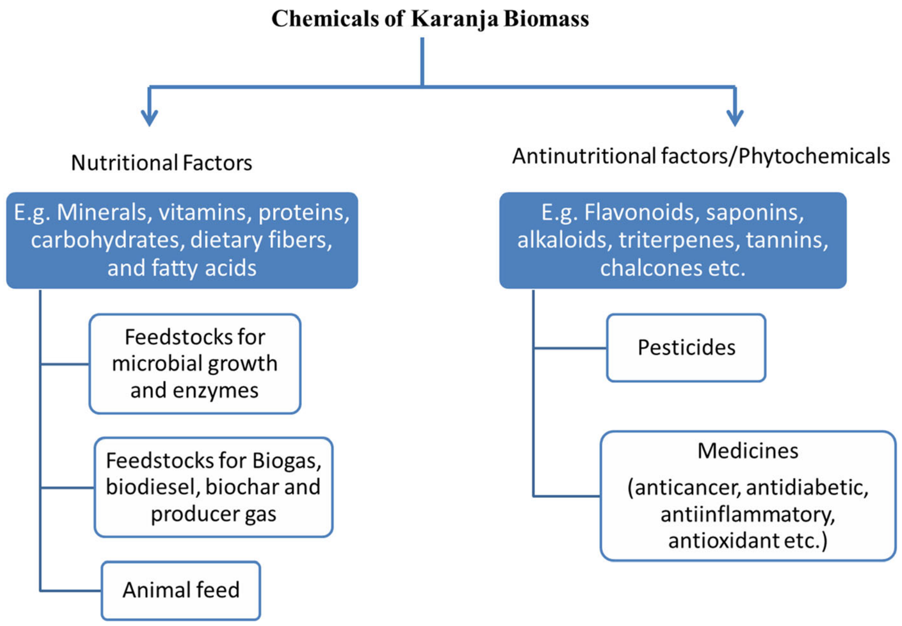


Fig. 2 Potential applications of Karanja biomass on the basis of its chemical constituents

these radicals, antioxidants compounds are required (Phaniendra et al. 2015). It has been reported that the presence of secondary metabolites like phenolics, terpenoids, flavonoids, etc. in various parts of the *M. pinnata* tree are the responsible compound for the most potent antioxidant property (Muqarrabun et al. 2013). Priya et al. (2016), reported that biosynthesis of metal nanoparticles developed from *P. pinnata* leaf extracts are potential natural antioxidants having reliable reducing power and can be essential for health preservation against oxidative stress-related degenerative diseases, such as cancer.

Vadivel and Biesalski (2011) reported that seed extract exhibited high levels of ferric reducing/antioxidant power (FRAP, 1179 mmol Fe(II)/mg extract), radical scavenging activity (54.64%), superoxide (54.53%) and also found to have inhibited effects against β-carotene degradation (41.13%). Amongst the plant parts tested, it has been found that extracts of barks contain more antioxidants power as compared to the other parts. A study conducted by Sajid et al. (2012) confirmed that the maximum extraction yield of antioxidant components was obtained from bark (16.31%), as compared to leaves (11.42%) and seeds (21.51%). Also, its extract contained higher levels of total phenolics (6.94 g GAE/100 g DW), total flavonoids (3.44 g CE/100 g DW), and DPPH radical scavenging activity having an IC_{50} value of 3.21 µg/ml. However, their flower extracts also possess remarkable antioxidant activity, and it is reported that aqueous flower extract exhibits high hydroxyl free radical scavenging inhibition capacity (Kumar et al. 2016). In contrast, Hazra et al. (2011a, b) compared the leaf, seed, and flower extracts and proclaimed the best antioxidant activity of leaf extracts.

Such antioxidant activities in plant parts are reported to be associated with the secondary metabolites explored in extracts. Several compounds found in this species are reported to exhibit antioxidant activity, for example, flavones (methylenedeoxy flavones and furano-flavone), a chalcone (pongamol), two triterpenes (cycloart-23-ene-3β-25diol and Lupeol) and an aromatic carboxylic acid (pyperonylic acid), in several studies, demonstrated significant antioxidant activity (Rao et al. 2009; Badole et al. 2011; Muqarrabun et al. 2013). The marker compound of this species, i.e., karanjin (furanoflavone), also found to exhibit strong effects against inhibition of oxidative stress, due to the presence of anti-oxidative enzymes such as catalase, peroxidase, and superoxide dismutase and by the normalization of lipid peroxidation (Vismaya et al. 2011).

Table 1 Medicinal uses of Karanja biomass

Plant part	Bioactive molecule responsible	Activity	Medicinal properties	References
Seed	Secondary metabolites such as phenols, flavonoids, etc.	Antioxidant activity	The extract exhibited high levels of ferric reducing power and radical scavenging activity	Vadivel and Biesalski (2011)
Roots	Flavone and chalcone	Anti-inflammatory effects	Out of the 52 derivatives isolated, tunicatachalone, isocordoin, 3,4,2,4 tetramethoxy chalcone, 2,4,dihydroxy-3,4-dimethoxychalcone exhibited strongest anti-inflammatory activity against nitric acid production in a microglial cell with an IC50 value in the range of 5.3–8.1 µM	Wen et al. (2018)
Seeds	Furano-flavonoid	Anti-ulcer activity	Karanjin inhibited 50 and 74% of ulcers induced by swim stress in rat models at 10 and 20 mg/kg body weight, respectively	Verma et al. (2011)
Leaves	Not mentioned	Immune modulatory	The aqueous extract induced higher production of nitric oxide in RAW 264.7 cells	Manikannan et al. (2011)
Stem bark	Not mentioned	Neuro-protective activity	Ethanol extract of stem bark (200 and 400 mg/kg) was administered orally to rats, significantly reduced the monosodium glutamate-induced excitotoxicity by decreasing the level of Ca^{+2} and Na^{+} with a concomitant increase in the level of K^{+}	Swamy et al. (2013)
Seeds	Karanjin	Anti-Alzheimer's activity	Karanjin decreased the transfer latency time in a dose-dependent manner when Swiss albino rats were fed orally with Karanjin (25 and 50 mg/kg bodyweight)	Saini et al. (2017)
Stem bark	Not mentioned	Anti-diabetic	Extract administered at 100 mg/kg significantly decreased blood glucose level, and improved oxidative stress in diabetic rats	Badole et al. (2015)
Seeds	Flavonoid (Karanjin)	Anti-Cancer effects	Inhibitory effects against human cancer cell lines MCF-7 and HeLa	Arulvasu et al. (2012)
Flower	Not mentioned	Anti-microbial activity	Extracts in the form of aqueous, ethanol and fresh juice exhibited effective antibacterial activity against *E. coli*	Kavitha et al. (2014)
Bark, leaves, and seeds	Phenolic acids and flavonoids	Anti-microbial activity	Bark extracts showed lower IC_{50} values (3.21–10.01 µg/ml) indicating higher radical scavenging activity, as compared to leaves (IC_{50} values 4.42–16.46 µg/ml) and seeds (IC_{50} values 15.7–38.0 µg/ml) extracts	Sajid et al. (2012)
Leaf, bark, flower, and root	Secondary metabolites like Saponins, alkaloids, flavonoids, triterpenes, tannins, etc.	Anti-malarial activity	Excellent activity against *Plasmodium falciparum* (3D7 strain) and *P. berghei* malaria parasite	Satish and Sunita (2017)

Anti-inflammatory property

Inflammation generally occurs due to the damage to the living tissues from bacterial, fungal, and viral infections. However, the inflammatory activity is a series of responses in the body which aims to localize, eliminate, and remove the damaged tissue and to heal the affected organ, tissue or system (Oguntibeju 2018). It has been reported that karanjin possesses anti-inflammatory effects against several kinds of ulcers. Karnajin extracted from the seeds could positively inhibit swim stress-induced ulcers in rats by 50 and

74% when administered at 10 and 20 mg/kg body weight. Patel and Trivedi (2017) also concluded that karanjin has the potential to cure colitis. They reported when pure karanjin was administered to colitic mice in two different concentrations 100 and 200 mg/kg for seven consecutive days, it significantly and dose-dependently ameliorates the visible damage. It could be due to that karanjin helps in the reduction of the myeloperoxidase activity, which catalyzes the formation of hypochlorous acid, a potent cytotoxic oxidant, and also significantly decreases the nitric oxide production (Patel and Trivedi 2017). It has also been reported that the presence of flavonoids, triterpenes, carotenoids, and saponins in the extracts of Karanja seeds are responsible for anti-ulcerative properties (Patil et al. 2010).

Anti-diabetic property

In today's era, diabetes is one of the foremost public health problems, which is a metabolic disorder caused due to impaired insulin secretion and/or insulin action (International Diabetes Federation 2015). Compounds extracted from plants play an essential role in curing diabetes. It has been investigated that chemical constituents like karanjin, pongamin, pongamol, etc., have anti-hyperglycemic activity (Tamrakar et al. 2008). Badole et al. (2015) revealed that stem bark extracts of *M. pinnata* (100 mg/kg, per oral) treatment significantly reduced the blood glucose levels in streptozotocin-nicotinamide induced diabetes in Sprague–Dawley rats. Extracts reduced the blood glucose levels because of their ability to stimulate the secretion of insulin from the surviving pancreatic β cells. Also, in their study, the preliminary phytochemical analysis of extracts indicated the presence of alkaloids, terpenoids, triterpenes, flavonoids, steroids, and volatile oils. Another study revealed Karanja leaf extracts as a potential drug to control diabetes (Sikarwar and Patil 2010). Ethanolic and aqueous extracts of Karanja leaves when studied in comparison with a known anti-diabetic drug glibenclamide in experimental diabetic rats, showed significant ($P < 0.001$) antidiabetic activity, with a blood glucose levels of 155.83 ± 11.211 mg/dl (ethanolic extracts) and 132.00 ± 4.955 mg/dl (aqueous extracts) in comparison to diabetic control (413.50 ± 4.752 mg/dl) respectively. Similarly, petroleum ether extract of stem bark of *M. pinnata* showed positive antihyperglycaemic activity, administration of 25, 50, 100, 200 and 400 mg/kg to alloxan-induced diabetic mice showed a significant reduction in serum glucose level (Badole and Bodhankar 2009). On the other hand, Punitha and Manoharan (2006) inferred that oral administration of ethanolic extract of *M. pinnata* flowers (300 mg/kg, body weight) to the alloxan-induced diabetic rats enhances anti-hyperglycemic, anti-lipid peroxidative effects.

Neuroprotective property

Neuronal cells are sensitive to the oxidative stress caused by free radicals as they lack internal antioxidant defense mechanisms (Masilamani et al. 2017). Thus, in view to combat and prevent neural damage, natural products rich in antioxidants are used as preventive measures. Scientists have also explored the neuroprotective role of *M. pinnata* extracts. A clinical study revealed that the stem bark extract of Karanja significantly reduced the excitotoxicity in albino rats induced by Monosodium glutamate neurotoxicity. It was observed that oral administration of ethanol extract at 200 and 400 mg/kg reduced the excitotoxicity by decreasing the level of Calcium and sodium ions with a simultaneous increase in the concentration of potassium ions, levels of Serum gamma-aminobutyric acid in rats' models (Swamy et al. 2013). It has been evident that the accumulation of high levels of Ca, Na, and low levels of K intracellularly trigger the mitochondrial dysfunction and free radical generation resulting in neurotoxicity. According to Nobre-Junior et al. (2009), extracts containing furano-flavonoids and chalcones exert neuroprotective activity in various neurodegenerative diseases; this could be one of the reasons for this property in Karanja plant too.

Anti-cancer property

As per the data of India Council of Medical Research (ICMR), about 1300 patients die every day in India due to cancer (NCRP Report 2017). Cancer is nothing but a stage where cells start to grow uncontrollably. It has been reported that specific secondary metabolites like flavones possess the anticancerous property and help in the cure of the disease. Nagaprashantha et al. (2011) found that flavones exhibit anti-proliferative, anti-angiogenic, and pro-apoptotic effects in carcinoma of prostate (CaP) cells (PC-3, DU-145, and

LNCaP). According to a study conducted by Arulvasu et al. (2012), *M. pinnata* seed oil extracts also possesses the anti-cancer property against human cancers. They reported that seed oil extracts of Karanja exhibited high cytotoxic property against the human cell lines MCF-7 (Human breast cancer cell line) and HeLa (Cervix). Both the cells were treated with or without the seed oil extracts at a concentration ranging from 2 to 10 mg/ml to check the cell viability. Results indicated a significant decrease in cell viability. As a confirmatory test, DNA fragmentation was also measured, which again showed high DNA fragmentations in cell lines with Karanja extracts indicating strong inhibitory effects against human cancer. George et al. (2010) also concluded that *M. pinnata* extracts possess high inhibitory actions against human pancreatic cancer. The methanolic extracts of the *M. pinnata*, when presented as the fraction of Panc-1 cell survival in comparison to controls, the extract exhibited high anti-proliferation activity of 0.1470.07 fraction of Panc-1 cell survival. The presence of various classes of flavonoids in *M. pinnata* extracts could be one of the primary reasons behind the anti-cancerous property of this medicinal plant.

Miscellaneous medicinal properties

The aqueous extract of Karanja leaves showed immuno-modulating activity demonstrated by the enhanced production of nitric oxide activity by the RAW 246.7 cells (Manikannan et al. 2011). The methanolic extract of Karanja biomass (dried leaves, bark, flowers, and roots) exhibited anti-plasmodial properties against *Plasmodium falciparum* (3D7 strain) and *P. berghei.* The extract at the concentration of 1000 mg/kg b.wt./day showed 83.90, 87.47, and 94.67% of chemo-suppression during Suppressive, Repository, and Curative tests respectively (Satish and Sunita 2017). The anti-microbial activity of Karanja biomass is also well documented. The aqueous methanolic extract of bark showed maximum anti-microbial activity against a set of common pathogenic microorganisms, which includes Gram-negative bacteria: *Pseudomonas aeruginosa*, *P. stutzeri*, *Escherichia coli,* and fungi: *Aspergillus oryzae*, *A. niger*, and *Fusarium solani* (Sajid et al. 2012). A comparative study revealed extract (aqueous, ethanol and fresh juice) of Karanja flowers more efficient in exhibiting 65.25% more antibacterial activity against *E. coli* than *M. oleifera* (Kavitha et al. 2014).

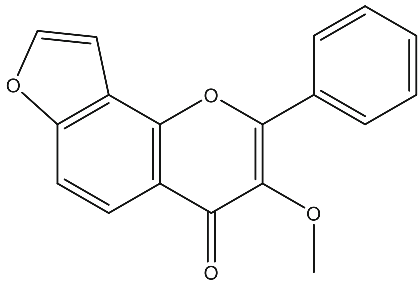
The majority of the phytochemicals that renders above mentioned medicinal properties to Karanja biomass belongs to the class flavonoids (flavones, flavans, and chalcones) while some are terpenes and carboxylic acids. Some of the major metabolites of *M. pinnata* representing an individual chemical class are shown in Fig. 3.

Agricultural applications

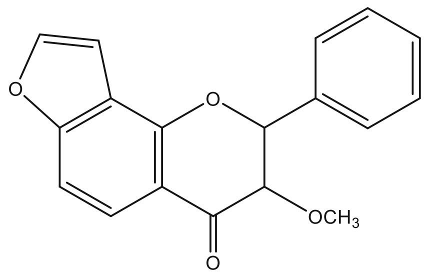
The use of oil cakes as organic manures, due to its richness in NPK content, has been in practice in the agriculture field for many decades. From improving rhizosphere health to enhancing plant growth parameters, oil cakes as fertilizers have been reviewed intensively on almost all crops. However, the biomass has also been applied or valorized as biopesticides due to the presence of toxic phytochemicals. Recently, the biomass has also been promoted as a phytoremediator of heavy metals, thereby enhancing the production in agriculture. From a veterinary point of view, the Karanja deoiled cake has been detoxified by various means and served as a protein supplement in animal feed.

Pesticidal activities

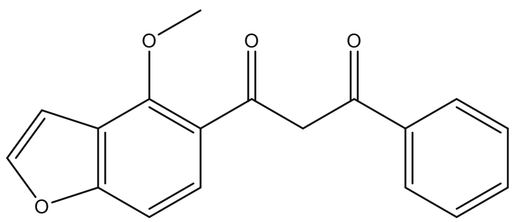
Phytochemical biopesticides hold great value for sustainable pest management in lieu of significant drawbacks of synthetic pesticides. *M. pinnata* possesses several toxic constituents (discussed elsewhere) due to which it has gained attention as potential pesticides (Walia et al. 2017; Kalra and Kaushik 2015) (Table 2). The pesticidal effect of Karanja oil on whiteflies (*Trialeurodes vaporariorum*) on *Chrysanthemum* plants has been reported (Pavela and Herda 2007b). A bioformulation (PONNEM) of Karanja oil in combination with neem oil showed oviposition deterrent effect against insect pests *Helicoverpa armigera* and *Spodoptera litura* (Packiam et al. 2012). Later, the same product was converted into an advanced nanoformulation through cross-linkage with chitosan nanoparticles, and the resultant product showed 88.5% antifeedant activity and 90.2% larvicidal activity against *H. armigera* (Paulraj et al. 2017). A comparative study of silver and gold nanoparticle of



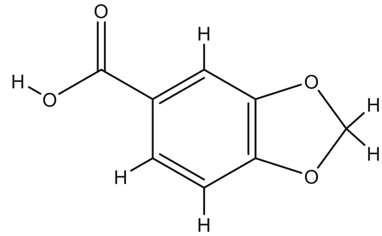
(a) Karanjin



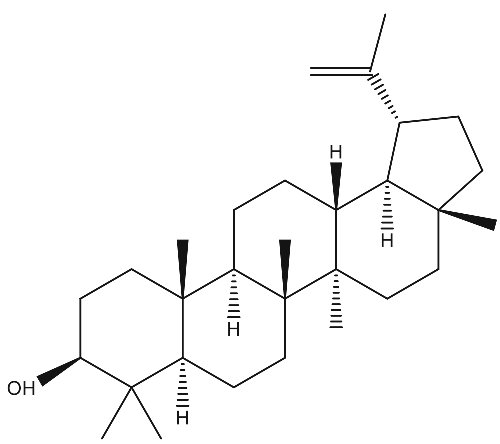
(d) Pongapin



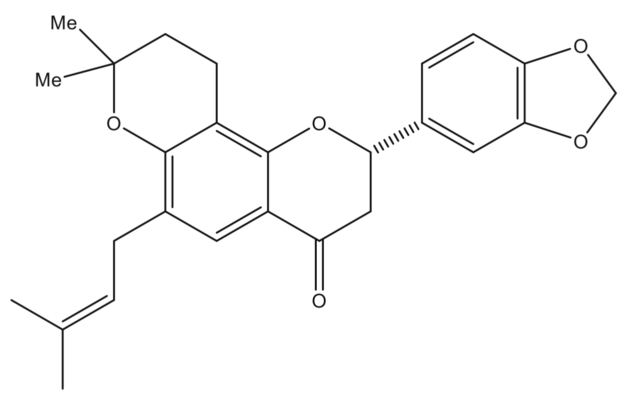
(b) Pongamol



(e) Pyperonylic acid



(c) Lupeol



(f) Pongamone C

Fig. 3 Chemical Structure of major secondary metabolites of *M. pinnata*. The majority of the phytochemicals are derivatives of flavonoids i.e. flavones (Karanjin, Pongapin), flavans (Pongamone C), chalcones (Pongamol), and miscellaneous like triterpenes (Lupeol) and carboxylic acid (Pyperonylic acid)

Karanja oil revealed the better pesticidal efficacy of the latter, against hairy caterpillar, *Pericalia ricini* (Sahayaraj et al. 2016). Both Pongam oil and karanjin (a furanoflavonol) effectively inhibited the growth of rice weevil, *Sitophilus oryzae* (Biswas and Biswas 2006). Karanjin has been investigated for its deterrent

Table 2 Pesticidal properties of Karanja biomass

S. no.	Active ingredient	Pests controlled	Efficacy	References
1.	Karanja Oil (2% v/v)	*Trialeurodes vaporariorum*	99.33%-Repellency 99.63% deterrence	Pavela and Herda (2007a, b)
2.	Karanaj oil in combination with neem oil (20 µl/l)	*Helicoverpa armigera* *Spodoptera litura*	68.12% deterrence 77.48% deterrence	Packiam et al. (2012)
3.	Karanja oil, neem oil with chitosan nanoparticles (0.3% v/v)	*Helicoverpa armigera*	88.5% antifeedant activity 90.2% larvicidal activity	Paulraj et al. (2017)
4.	Karanja oil (0.03% v/v)	*Pericalia ricini*	60% mortality	Sahayaraj et al. (2016)
5.	Karanjin (0.25–0.5 g/ml)	*Odontotermes obesus*	100% mortality	Verma et al. (2011)
6.	Karanjin (0.25% w/v)	*Lipaphis erysimi*	100% mortality	Mondal et al. (2010)
7.	Leaf extract with ZnO nanoparticles (25 µg/ml)	*Callosobruchus maculatus*	100% mortality	Malaikozhundan and Vinodhini (2018)
8.	Seed kernel (50 ml/l)	*Amrasca devastans* *Aphis gossypii*	34.66–35.72% reduction in aphid population	Vinodhini and Malaikozhundan (2011)
9.	Seed extracts (1% w/v)	*Earias vittella*	> 65% and 75% first instar larval mortality	Reena and Singh (2007)
10.	Karanja + Jatropha de-oiled cake (1:1)	*Aedes aegypti* *Tribolium castaneum*	96% mortality 88–100% mortality	Pant et al. (2016) Pant et al. (2014)

activity against termites, *Odontotermes obesus* (Verma et al. 2011). The insecticidal property of karanjin against mustard aphid, *Lipaphis erysimi*, was enhanced by altering the chemical structure into karanj ketone oxime esters with LC_{50} of 0.048% (Mondal et al. 2010).

Besides the oil, the pesticidal efficacy of other parts of Karanja biomass has also been investigated. Nanopesticidal formulation of Karanja leaf extract developed with ZnO nanoparticles has been effective against pulse beetle, *Callosobruchus maculatus* (Malaikozhundan, and Vinodhini 2018). The pesticide significantly reduced the α-amylase and cysteine protease activity of *C. maculatus*. Aqueous extract of Karanja seed kernel (5% w/w) showed antifeedant activity against leafhopper, *Amrasca devastans,* and aphid, *Aphis gossypii* (Vinodhini and Malaikozhundan 2011). Hexane fraction of both mature and immature methanolic seed extracts caused disruptive behavioral and physiological activities in *Earias vittella* (Reena and Singh 2007). The pesticidal activity of deoiled cake of *M. pinnata* against *Aedes aegypti* larvae (Pant et al. 2016), and *Tribolium castaneum* (Pant et al. 2014) have been reported. The use of non-edible oil cakes, including Karanja as an organic amendment to control phytoparasitic nematodes, has extensively been reviewed (Akhtar and Malik 2000; Oka 2010). Barring plant-parasitic nematodes where pesticidal activity has been accredited to the release of simpler molecules like ammonia and organic acids during decomposition of deoiled cake (Oka 2010), the significant impact of Karanja biomass as phytopesticide is primarily because of karanjin (Walia et al. 2017). The toxic molecule acts as potent feeding and oviposition deterrent against several field insects and mites. The antifeedant activity of karanjin has been linked to its ability to suppress ecdysteroids (Gonzalez-Coloma et al. 2013) and inhibit protease activity (Malaikozhundan and Vinodhini 2018). Though a potent pesticide, karanjin has been found to have minimal cytotoxic side effects on humans while the mild inhibitory impact on non-target microflora of soil (Raghav et al. 2019). Thus, the use of Karanja based phytopesticide is not only effective and competitive but also safe and sustainable.

Phytoremediation

The utility value of *M. pinnata* biomass as a phytoremediation tool for toxic contaminants has been investigated. Karanja tree is indigenous to the Indian environment and offers more tolerance to heavy metals in soil compared to other tree species. Further, linking to the bioenergy potential, phytoremediation using the Karanja tree becomes all the more holistic and sustainable (Pandey et al. 2016). Some believe that phytoremediation through energy crops would not only avoid the food/fodder-fuel conflict but also provide sustenance to a bio-based economy in developing nations (Tripathi et al. 2016). Reclamation of polluted and abandoned land is an added advantage of the 'phytoremediation by energy crop' approach (Abhilash et al. 2013). Experiments on Karanja seedlings revealed the ability of the biomass to tolerate Arsenic (As) up to 0.2–1.0 mM without showing an adverse effect on its growth and chlorophyll content (Kumar et al. 2017a, b). In another study, thermally activated Karanja deoiled cake removed 94.12% of As (III) in the countercurrent fluidized bed column (De et al. 2019). Karanja plants inoculated with plant growth-promoting isolate, *Bradyrhizobium liaoningense* remediated mine tailings polluted with iron–vanadium–titanium oxide (Yu et al. 2017). The symbiotic association enhanced the remediation potential as the plant accumulated 1753.2 and 3111.0 mg/kg in the roots and shoots of *M. pinnata*, respectively. An experiment with biosorbent prepared from deoiled seeds of *Pongamia* demonstrated successful remediation of water contaminant, chromium in the form of Cr(VI) ions in an aqueous medium (Rangabhashiyam et al. 2019).

Animal feed

The presence of anti-nutritional factors (phytates, tannins, and protease inhibitors, glabrin and karanjin) limits the use of Karanja oil cake as feed for cattle. However, after proper processing, a higher concentration of Karanja cake can be included in the diet of livestock (Soren and Sastry 2009). Treatment of Karanja cake with dilute acid (2% HCl) for one hour at room temperature removes tannins, phytates, and trypsin inhibitors up to 54, 72.5, and 74%, respectively (Vinay and Kanya 2008). Conversely, Habib et al. (2016) observe no improvement in the performance of broilers when fed with Karanja seed cake detoxified after treatment with dilute alkali or acid. Detoxified Karanja cake obtained through water washing proved to be a promising protein supplement for male lambs as the diet containing 50% N replaced by detoxified Karanja cake did not affect the gross and histopathological architecture of vital organs (Soren et al. 2017). Karanja seeds treated with aqueous methanol mixture removed the toxic constituents and became suitable to partially substituted soybean meal (9% in a concentrated mixture) as livestock feed for lambs (Rao and Kumar 2015). Incorporation of detoxified Karanja seed cake at 5.85% of total mixed ratio (maize grain, deoiled soybean meal, urea, molasses, mineral mixture, and salt) improved the milk yield of crossbred dairy cows. However, comparatively, authors observed the performance of Karanja inferior to deoiled Neem seed cake (Raj et al. 2016). Alkali processed Karanja seed cake (1.5% NaOH) supplemented with 0.2% methionine replaced 12.5% nitrogen of Soybean meal in broiler diets and showed no adverse effect on carcass characteristics and sensory attributes (Panda et al. 2007).

Industrial applications

Any industrial process is deemed sustainable if the nutrient (substrate) input is a low cost yet widely available. Both oil and oil cakes of the Karanja tree are a cheap and abundant source of fats, proteins, and carbohydrates and therefore, can serve as a potential tool for an economically viable bioprocess industry. The general characterization of Karanja oil and deoiled cake is given in Tables 3 and 4, respectively. The ability of the Karanja biomass as a renewable feedstock was investigated for industrial applications to keep the economics of bioprocess in check.

Bioenergy

Depleting fossil fuels and rising alarms over climate change and greenhouse gas emissions have persuaded the energy sectors across the globe to look for alternate clean and green energy concepts. Under this approach, various plant and algal biomass have been exploited as feedstocks for the production of renewable energy, often termed as bioenergy. India backs non-edible oilseed tree-based biofuel programs as a long-term

Table 3 Characteristics of Karanja oil (Kumar et al. 2018; Dwivedi and Sharma 2014)

S. no.	Properties	Karanja oil
1.	Kinematic viscosity (cSt) at 40 °C	41.71
2.	Density (kg/m^3)	911
3.	Flashpoint (°C)	241
4.	Fire point (°C)	260
5.	Pour point (°C)	5
6.	Cloud point (°C)	15
7.	Calorific value (MJ/kg)	41.83
8.	Saponification value	190
9.	Iodine value	87
10.	Carbon residue (%)	0.71
11.	Fatty acid (%)	
	(a) Total saturated acid	20.5
	(b) Total unsaturated acid	79.5

investment that has the potential to serve as sustainable feedstocks (Rasool and Hemalatha 2016). The seed oil of *P. pinnata* is non-edible due to the presence of toxic compounds such as karanjin and pongamol (Marriboina et al. 2017). Together with the fact that the oil content is very high ($\sim$ 35%) but mostly underutilized (Dwivedi and Sharma 2016), Karanja tree becomes very promising and potential biomass for bioenergy in context to India and other South-Asian countries.

Feedstock for biodiesel production

Karanja seeds contain 27–40% (w/w) oil, which is yellowish orange with an unpleasant aroma. Although, various factors are responsible for the quality of biodiesel produced from Karanja oil viz., viscosity, flash point, calorific value, saponification value, specific gravity, and acid value the detrimental factor is free fatty acids (FFA) content (Dwivedi and Sharma 2014). Since FFA content is very high in Karanja oil, biodiesel is preferably produced through a two-step transesterification process wherein Karanja oil undergoes acid esterification before alkali transesterification (Joshi et al. 2016). Under supercritical conditions, both steps can be carried out simultaneously to minimize the duration of the process (Takase et al. 2015) while some suggested use of microwave and CaO as a heterogeneous catalyst to enhance the transesterification process (Joshi et al. 2015). Karanja oil, like any other vegetable oils, is highly viscous and, therefore, unsuitable for direct use in a diesel engine. The transesterification process addresses this issue and produces quality Karanja oil methyl ester (biodiesel) cost-effectively. Pyrolysis, microemulsion, and blending are other methods for the production of biodiesel from Karanja oil (Patel and Sankhavara 2017). In recent years, efforts are being made to market Karanja oil-based biodiesel as a commercial option over mineral fuels. However, the critics are still apprehensive about its production cost and oxidation stability. Though the use of various anti-oxidants (like pyrogallol) in biodiesel is being suggested to improve the oxidation stability, cost-analysis of biodiesel production is still warranted at different research levels (Mofizur et al. 2016).

Feedstock for bioethanol and biogas generation

The exploitation of Karanja oil as medicine and feedstock for biodiesel leads to the generation of 120,000–130,000 tons/annum de-oiled seed residue (Muktham et al. 2016a). The residual deoiled cake of *M. pinnata* being a cellulosic rich biomass with round the year availability at a cheaper rate, makes it a promising feedstock for bioethanol and biogas production. Like biodiesel, both bioethanol and biogas are being proclaimed as green, non-toxic, biodegradable biofuel options. Bioethanol from Karanja deoiled cakes considered to be a second-generation biofuel as

Table 4 Characteristics of Karanja deoiled cake (Sharma et al. 2013a, b)

S. no.	Parameters	Karanja deoiled cake
1.	Crude protein (%)	30.43
2.	Crude fibre (%)	6.5
3.	Ash (%)	5.2
4.	Carbon (%)	42.26
5.	Nitrogen (%)	4.87
6.	Phosphorus (%)	0.89
7.	Potassium (%)	1.3
8.	C:N ratio	8.68:1
9.	pH	5.5

the feedstock is non-food material and quell the "food for fuel" issues often related to first-generation biofuel (Robak and Balcerek 2018). Acid hydrolysis is a widely spread pretreatment method that converts cellulose and hemicellulose of deoiled cake into soluble sugars using dilute acids (Doshi and Srivastava 2013; Sharmada et al. 2016). In one such study, Karanja deoiled cake was pretreated with different acids (H_2SO_4, HCl, and H_3PO_4) at varying concentrations to obtain a high yield of glucose (Radhakumari et al. 2017). Treating the Karanja deoiled cake with various in-house lignocellulosic enzymes isolated from microbial isolates grown over the same substrate has also been reported (Radhakumari et al. 2017).

There is a broad scope of using Karanja deoiled cake as co-substrate during anaerobic digestion for the production of biogas. Karanja deoiled cake when mixed with various proportions of cow dung, shown to produce 73% methane in biogas with a heating value of 408 27.5 MJ/kg and approximately 6.5 kW/m^3 of the energy content (Barik and Murugan 2015). On the contrary, Chandra et al. (2012) preferred Karanja deoiled cake as sole substrate and reported 15–20% more methane in the biogas compared to biogas from cattle dung. The authors reasoned the presence of higher volatile solids content (85.3%) in Karanja deoiled cake for the better performance as feedstock for biomethanation process. From an Indian perspective, valorization of deoiled cake holds the key in improving the economics of biodiesel production and providing a sustainable solution for waste disposal problems through bioethanol and biogas production.

Feedstock for biochar and producer gas (syngas)

Thermal decomposition of Karanja deoiled cake (pyrolysis) in the absence of oxygen yields carbon-rich biochar and bio-oil, also known as pyrolytic oil (Zhu et al. 2018). Besides being utilized as a solid eco-friendly biofuel, biochar is also used as an organic amendment to improve soil fertility (Song et al. 2014) and adsorbent for pollutant removal (Manyà 2012). Thermogravimetric analysis revealed that the slow pyrolysis of Karanja deoiled cake at 450–500 °C produces the biochar with enhanced carbonization (Muktham et al. 2016b). Chutia et al. (2014) conducted a pyrolysis experiment of KDOC in lab-scale fixed-bed pyrolyzer and obtained highly basic biochar at 500 °C with a heating rate of 40 °C/min. Kumar and Pant (2015) exploited modified hydrothermal treatment to convert KDOC into biochar with high calorific values (24.7–26.3 MJ/kg). Pyrolysis of small-sized (125–425 μm) Karanja deoiled cake at 500 °C using zeolite Y as catalyst gave the 99% hydrocarbon yield (Soongprasit et al. 2017).

Gasification of biomass converts lignocellulosic matter into producer gas that can be directly used for the production of electricity and liquid fuels (Chutia et al. 2014). The process is simple compared to pyrolysis and is considered as low carbon emission technology. An investigation during thermochemical gasification of Karanja shell (covering of seeds) revealed the correlation between pelletization and gasification efficiency (Prasad et al. 2015). Pellet size of 17 mm diameter failed to achieve complete gasification (73%), while 11.5 mm pellet of Karanja shells produced 95% gasification efficiency. Producer gas produced from an 11.5 mm pellet had a calorific value of 4.66 MJ/Nm^3. Deoiled cake of Karanja did not prove to be the suitable feedstock for gasification as both the pellet size (17 and 11.5 mm) failed to achieve complete gasification (Prasad et al. 2014). During oxygen-steam gasification of Karanja press seed cake, heating the feedstock at 1000 °C produced the syngas with 95% cold gas efficiency and ~ 12 MJ/Nm^3 lower heating value (Dhanavath et al. 2018). Recently, biochar obtained from Karanja deoiled cake has been used as feedstock for the synthesis of production gas using the air gasification method in a fluidized bed reactor (Marshal et al. 2019).

Feedstock for the production of enzymes and metabolites

Industrial production of enzymes takes place through fermentation (solid or submerged) of substrate employing bacteria or fungi (Sivaramakrishnan and Gangadharan 2009). Deoiled cake of Karanja is rich in proteins, and different studies have investigated their viability as a substrate for various enzyme production. Sharma et al. (2014a) demonstrated the usefulness of Karanja deoiled cake as feedstock for protease production using entomopathogenic fungus *Paecilomyces lilacinus* 6029. In another study, the deoiled cake was used as the substrate to produce protease (9840 U/g DM) and lipase (1974 U/g DM) using *B. pumilus* SG2 (Sangeetha et al. 2011). The authors did not supplement the cake with any carbon or nitrogen source as the cake itself was found sufficient to produce an optimum quantity of targeted enzymes. Endophytic fungus *Colletotrichum gloeosporioides* showed lipase activity (983 U/g DM) using Karanja oil cake as a substrate (Balaji and Ebenezer 2008). The exploitation of deoiled cake as a growth substrate for the mass multiplication of biocontrol agents like *Paecilomyces lilacinus*, *P. variottii,* and *Trichoderma harzianum* has been investigated (Sharma et al. 2013a, b, 2014b; Arora et al. 2017; Singh et al. 2015). Research work indicates that KDOC is also a potential substrate for the production of secondary metabolites viz., fatty acids from *P. lilacinus* 6029 (Sharma et al. 2014a), dipicolinic acid from *P. variottii* (Arora et al. 2017), glycolipid (biosurfactant) from *Pseudomonas aeruginosa* AB4 (Hazra et al. 2011a, b), and iturin A from *B. amyloliquefaciens* RHNK22 (Kumar et al. 2017a, b).

Conclusion and future perspectives

Through the review, authors have presented the broader perspective of the Karanja tree besides serving as feedstock for biodiesel production. The multiple potential utilities of this legume have been credited to its rich nutritional and bioactive constituents. Further, the ability of the plant to tolerate abiotic stress and adapt to varied edaphic and ecological regions establishes the candidature of the Karanja tree to be promoted for afforestation programs. Henceforth, the focus shall now be on crop improvement through genetics. Research should be conducted to develop the genetically stable disease-free clones of this critical legume plant. High throughput sequencing and transcriptome analysis should be performed to elucidate the mechanisms behind the synthesis of fatty acids and other prominent phytochemicals and ways to enhance their expressions in the plant.

Acknowledgements The corresponding author greatly acknowledges the Department of Biotechnology (DBT), Government of India, for financial support (Grant No. BT/PR17530/NDB/39/552/2016).

References

Abhilash PC, Singh B, Srivastava P, Schaeffer A, Singh N (2013) Remediation of lindane by *Jatropha curcas* L: utilization of multipurpose species for rhizoremediation. Biomass Bioenergy 51:189–193

Akhtar M, Malik A (2000) Roles of organic amendments and soil organisms in the biological control of plant-parasitic nematodes: a review. Biores Technol 74:35–47

Arora K, Sharma S, Krishna SB, Adam JK, Kumar A (2017) Non-edible oil cakes as a novel substrate for DPA production and augmenting biocontrol activity of *Paecilomyces variotii*. Front Microbiol 8:753

Arulvasu C, Supriya SV, Babu G (2012) Anticancer activity of *Pongamia glabra* V. seed oil extract against selected human cancer cell lines. Int Res J Pharm 3:131–134

Badole SL, Bodhankar SL (2009) Investigation of antihyperglycaemic activity of aqueous and petroleum ether extract of stem bark of *Pongamia pinnata* on serum glucose level in diabetic mice. J Ethnopharmacol 123:115–120

Badole SL, Zanwar AA, Khopade AN, Bodhankar SL (2011) In vitro antioxidant and antimicrobial activity cycloart-23-ene-3β,-25-diol (B2) isolated from *Pongamia pinnata* (L. Pierre). Asian Pac J Trop Med 4(11):910–916

Badole SL, Chaudhari SM, Jangam GB, Kandhare AD, Bodhankar SL (2015) Cardioprotective activity of *Pongamia pinnata* in streptozotocin-nicotinamide induced diabetic rats. BioMed Res Int 2015:403291–403291

Bala M, Nag TN, Kumar S, Vyas M, Kumar A, Bhogal NS (2011) Proximate composition and fatty acid profile of *Pongamia pinnata*, a potential biodiesel crop. J Am Oil Chem Soc 88:559–562

Balaji V, Ebenezer P (2008) Optimization of extracellular lipase production in *Colletotrichum gloeosporioides* by solid state fermentation. Ind J Sci Technol 1:1–8

Barik D, Murugan S (2015) Assessment of sustainable biogas production from de-oiled seed cake of karanja-an organic industrial waste from biodiesel industries. Fuel 148:25–31

Belide S, Sajjalaguddam RR, Paladugu A (2010) Cytokinin preconditioning enhances multiple shoot regeneration in

Pongamia pinnata (L.) Pierre-a potential, non-edible tree seed oil source for biodiesel. Electron J Biotechnol 13:3–4
Biswas NP, Biswas AK (2006) Use of non-edible oils as grain protectant against rice weevil (*Sitophilus oryzae* L.) and their subsequent effect on germination. Adv Plant Sci 19:653–656
Chandra R, Vijay VK, Subbarao PMV, Khura TK (2012) Production of methane from anaerobic digestion of jatropha and pongamia oil cakes. Appl Energy 93:148–159
Chutia RS, Kataki R, Bhaskar T (2014) Characterization of liquid and solid product from pyrolysis of *Pongamia glabra* deoiled cake. Biores Technol 165:336–342
De D, Aniya V, Satyavathi B (2019) Application of an agro-industrial waste for the removal of As (III) in a counter-current multiphase fluidized bed. Int J Environ Sci Technol 16:279–294
Dhanavath KN, Shah K, Bhargava SK, Bankupalli S, Parthasarathy R (2018) Oxygen–steam gasification of karanja press seed cake: fixed bed experiments, ASPEN Plus process model development and benchmarking with saw dust, rice husk and sunflower husk. J Environ Chem Eng 6(2):3061–3069
Divakara BN, Alur AS, Tripati S (2010) Genetic variability and relationship of pod and seed traits in *Pongamia pinnata* (L.) Pierre., a potential agroforestry tree. Int J Plant Prod 4:131–141
Doshi P, Srivastava G (2013) Sustainable approach to produce bioethanol from Karanja (*Pongamia pinnata*) oilseed residue. Turk J Agric For 37:781–788
Dwivedi G, Sharma MP (2014) Prospects of biodiesel from *Pongamia* in India. Renew Sustain Energy Rev 32:114–122
Dwivedi G, Sharma MP (2016) Investigation of oxidation stability of *Pongamia* biodiesel and its blends with diesel. Egypt J Pet 25:15–20
George S, Bhalerao SV, Lidstone EA, Ahmad IS, Abbasi A, Cunningham BT, Watkin KL (2010) Cytotoxicity screening of Bangladeshi medicinal plant extracts on pancreatic cancer cells. BMC Complement Altern Med 10(1):52
Gonzalez-Coloma A, Reina M, Diaz CE, Fraga BM, Santana-Meridas O (2013) Natural product-based biopesticides for insect control. In: Reedijk J (ed) Reference module in chemistry, molecular sciences and chemical engineering. Elsevier, Amsterdam
Habib M, Ferdaus AJ, Islam MT, Hassin BM, Ali MS (2016) Performance of broiler fed on diet containing deoiled Koroch (*Pongamia pinnata*) seed cake treated with NaOH and HCl. Res Agric Livest Fis 3:323–329
Hazra B, Sarkar R, Biswas S, Mandal N (2011a) Antioxidant and iron chelating potential of *Pongamia pinnata* and its role in preventing free radical induced oxidative damage in plasmid DNA. Int J Phytomed 3:240–253
Hazra C, Kundu D, Ghosh P, Joshi S, Dandi N, Chaudhari A (2011b) Screening and identification of Pseudomonas aeruginosa AB4 for improved production, characterization and application of a glycolipid biosurfactant using low-cost agro-based raw materials. J Chem Technol Biotechnol 86:185–198
International Diabetes Federation (IDF) Diabetes atlas-7th edition (2015) http://www.diabetesatlas.org/resources/2015-atlas
Joshi G, Rawat DS, Lamba BY, Bisht KK, Kumar P, Kumar N, Kumar S (2015) Transesterification of Jatropha and Karanja oils by using waste egg shell derived calcium based mixed metal oxides. Energy Convers Manag 96:258–267
Joshi G, Rawat DS, Sharma AK, Pandey JK (2016) Microwave enhanced alcoholysis of non-edible (algal, jatropha and pongamia) oils using chemically activated egg shell derived CaO as heterogeneous catalyst. Biores Technol 219:487–492
Kalra R, Kaushik N (2015) Prospecting of oil and deoiled cakes of *Jatropha curcas* L. and *Pongamia pinnata* L. for pesticidal activity. In: Abstracts of papers of the American Chemical Society (250) 1155 16TH ST, NW, Washington, DC 20036 USA: American Chemical Society
Kavitha MT, Chaithra U, Kavya M, Bharathi S, Yogesh J, Sekar V (2014) Antibacterial activity of *Pongamia pinnata* and *Moringa oleifera* Lam flower extracts against selected bacterial strains and their comparative evaluation. Int Res J Pharm 5(7):593–596
Kumar D, Pant KK (2015) Production and characterization of biocrude and biochar obtained from non-edible de-oiled seed cakes hydrothermal conversion. J Anal Appl Pyrol 115:77–86
Kumar RSAR, Rajeswari R, Selvakumar M (2016) Study of *Pongamia pinnata* flower and seed extracts for their antioxidant and antibacterial activity. Indo Am J Pharm Res 6:6618–6621
Kumar D, Tripathi DK, Liu S, Singh VK, Sharma S, Dubey NK, Prasad SM, Chauhan DK (2017a) *Pongamia pinnata* (L.) Pierre tree seedlings offer a model species for arsenic phytoremediation. Plant Gene 11:238–246
Kumar PN, Swapna TH, Khan MY, Reddy G, Hameeda B (2017b) Statistical optimization of antifungal iturin a production from *Bacillus amyloliquefaciens* RHNK22 using agro-industrial wastes. Saudi J Biol Sci 24(7):1722–1740
Kumar D, Das T, Giri B, Verma B (2018) Characterization and compositional analysis of highly acidic Karanja oil and its potential feedstock for enzymatic synthesis of biodiesel. New J Chem 42:15593–15602
Malaikozhundan B, Vinodhini J (2018) Nanopesticidal effects *of Pongamia pinnata* leaf extract coated zinc oxide nanoparticle against the Pulse beetle, *Callosobruchus maculatus*. Mater Today Commun 14:106–115
Manikannan M, Balamurugan R, Varatharajan R, Dinesh S, Manickan E (2011) Nitric oxide induce IL-10, a CD4þ T Helper Type-2 (Th-2) cytokines in human PBMC. J Pharm Biomed Sci 7:1–6
Manyà JJ (2012) Pyrolysis for biochar purposes: a review to establish current knowledge gaps and research needs. Environ Sci Technol 46(15):7939–7954
Marriboina S, Sengupta D, Kumar S, Reddy AR (2017) Physiological and molecular insights into the high salinity tolerance of *Pongamia pinnata* (L.) pierre, a potential biofuel tree species. Plant Sci 258:102–111
Marshal JJS, Kumar TMN, Kennedy ZR, Sundari GK (2019) Air gasification of char drived from *Pongamia* de-oiled Cake in a fluidized bed reactor. Int J Mech Eng Technol 10:1571–1580
Masilamani T, Subramaniam T, Nordin N, Rosli R (2017) Neuroprotective effects of *Peltophorum pterocarpum* leaf

extract against hydrogen peroxide induced oxidative stress and cytotoxicity. Clin Phytosci 3(1):1–13

Mofijur M, Rasul M, Hyder J, Azad AK, Mamat R, Bhuiya MMK (2016) Role of biofuel and their binary (diesel–biodiesel) and ternary (ethanol–biodiesel–diesel) blends on internal combustion engines emission reduction. Renew Sustain Energy Rev 53:265–278

Mondal A, Walia S, Shrivastava C, Kumar B, Kumar J (2010) Synthesis and insecticidal activity of karanj ketone oxime and its ester derivatives against the mustard aphid (*Lipaphis erysimi*). Pestic Res J 22:39–43

Muktham R, Ball AS, Bhargava SK, Bankupalli S (2016a) Bioethanol production from non-edible de-oiled *Pongamia pinnata* seed residue-optimization of acid hydrolysis followed by fermentation. Ind Crops Prod 94:490–497

Muktham R, Ball AS, Bhargava SK, Bankupalli S (2016b) Study of thermal behavior of deoiled karanja seed cake biomass: thermogravimetric analysis and pyrolysis kinetics. Energy Sci Eng 4:86–95

Muqarrabun LMR, Ahmat N, Ruzaina SAS, Ismail NH, Sahidin I (2013) Medicinal uses, phytochemistry and pharmacology of *Pongamia pinnata* (L.) Pierre: a review. J Ethnopharmacol 150:395–420

Nagaprashantha LD, Vatsyayan R, Singhal J, Fast S, Roby R, Awasthi S, Singhal SS (2011) Anti-cancer effects of novel flavonoid vicenin-2 as a single agent and in synergistic combination with docetaxel in prostate cancer. Biochem Pharmacol 82:1100–1109

National Centre for Disease Informatics and Research Centre National Cancer Registry Programme (2017) Indian Council of Medical Research 22

Nobre-Junior HV, Oliveira RA, Maia FD, Nogueira MA, de Moraes MO, Bandeira MAM, Andrade GM, Viana GS (2009) Neuroprotective effects of chalcones from *Myracrodruon urundeuva* on 6-hydroxydopamine-induced cytotoxicity in rat mesencephalic cells. Neurochem Res 34:1066–1075

Oguntibeju OO (2018) Medicinal plants with anti-inflammatory activities from selected countries and regions of Africa. J Inflamm Res 11:307–317

Oka Y (2010) Mechanisms of nematode suppression by organic soil amendments: a review. Appl Soil Ecol 44:101–115

Packiam SM, Anbalagan V, Ignacimuthu S, Vendan SE (2012) Formulation of a novel phytopesticide PONNEEM and its potentiality to control generalist herbivorous lepidopteran insect pests, *Spodoptera litura* (Fabricius) and *Helicoverpa armigera* (Hübner) (Lepidoptera: Noctuidae). Asian Pac J Trop Dis 2:720–723

Panda AK, Sastry VRB, Mandal AB, Saha SK, Kumar A (2007) Physico-chemical carcass characteristics and sensory attributes of meat of broiler chickens fed diets incorporated with processed karanja cake. Indian J Poult Sci 42:257–263

Pandey VC, Bajpai O, Singh N (2016) Energy crops in sustainable phytoremediation. Renew Sustain Energy Rev 54:58–73

Pant M, Dubey S, Patanjali PK, Naik SN, Sharma S (2014) Insecticidal activity of eucalyptus oil nanoemulsion with karanja and jatropha aqueous filtrates. Int Biodeterior Biodegrad 91:119–127

Pant M, Sharma S, Dubey S, Naik SN, Patanjali PK (2016) Utilization of biodiesel by-products for mosquito control. J Biosci Bioeng 121:299–302

Patel RL, Sankhavara CD (2017) Biodiesel production from Karanja oil and its use in diesel engine: a review. Renew Sustain Eng Rev 71:464–474

Patel PP, Trivedi ND (2017) Effect of karanjin on 2, 4, 6-trinitrobenzenesulfonic acid-induced colitis in Balb/c mice. Indian J Pharm 49:161–167

Patil P, Prasad K, Nitin M, Sreenivasa RK (2010) Anti-ulcer and anti-secretory properties of the *Pongamia Pinnata* root extract with relation to anti-oxidant studies. Res J Pharm Biol Chem Sci 1:235–244

Paulraj MG, Ignacimuthu S, Gandhi MR, Shajahan A, Ganesan P, Packiam SM, Al-Dhabi NA (2017) Comparative studies of tripolyphosphate and glutaraldehyde cross-linked chitosan-botanical pesticide nanoparticles and their agricultural applications. Int J Biol Macromol 104:1813–1819

Pavela R, Herda G (2007a) Effect of pongam oil on adults of the greenhouse whitefly *Trialeurodes vaporariorum* (Homoptera: Trialeurodidae). Entomol Gen 30:193–201

Pavela R, Herda G (2007b) Repellent effects of pongam oil on settlement and oviposition of the common greenhouse whitefly *Trialeurodes vaporariorum* on chrysanthemum. Insect Sci 14:219–224

Pavithra HR, Shivanna MB, Chandrika K, Prasanna KT, Gowda B (2010) Seed protein profiling of *Pongamia pinnata* (L.) Pierre for investigating inter and intra-specific population genetic diversity. Int J Sci Nat 2:246–252

Phaniendra A, Jestadi DB, Periyasamy L (2015) Free radicals: properties, sources, targets, and their implication in various diseases. Ind J Clinic Biochem 30:11–26

Prasad L, Subbarao PMV, Subrahmanyam JP (2014) Pyrolysis and gasification characteristics of *Pongamia* residue (de-oiled cake) using thermogravimetry and downdraft gasifier. Appl Therm Eng 63:379–386

Prasad L, Subbarao PMV, Subrahmanyam JP (2015) Experimental investigation on gasification characteristic of high lignin biomass (*Pongamia* shells). Renew Energy 80:415–423

Priya RS, Geetha D, Ramesh PS (2016) Antioxidant activity of chemically synthesized AgNPs and biosynthesized *Pongamia pinnata* leaf extract mediated AgNPs: a comparative study. Ecotoxicol Environ Saf 134:308–318

Punitha R, Manoharan S (2006) Antihyperglycemic and antilipidperoxidative effects of *Pongamia pinnata* (Linn.) Pierre flowers in alloxan induced diabetic rats. J Ethnopharm 105:39–46

Radhakumari M, Taha M, Shahsavari E, Bhargava SK, Satyavathi B, Ball AS (2017) *Pongamia pinnata* seed residue: a low cost inedible resource for on-site/in-house lignocellulases and sustainable ethanol production. Renew Energy 103:682–687

Raghav D, Mahanty S, Rathinasamy K (2019) Biochemical and toxicological investigation of karanjin, a bio-pesticide isolated from *Pongamia* seed oil. Pesticide Biochem Physiol 157:108–121

Raj DN, Ramana JV, Rao SBN, Kumar DD, Suryanarayana MVA, ReddyYR Prasad KS (2016) Effect of incorporation of detoxified karanja (*Pongamia pinnata*) and neem (*Azadirachta indica*) seed cakes in total mixed rations on milk yield, composition and efficiency in crossbred dairy cows. Indian J Anim Sci 86:489–492

Rangabhashiyam S, Sayantani S, Balasubramanian P (2019) Assessment of hexavalent chromium biosorption using biodiesel extracted seeds of *Jatropha* sp., *Ricinus* sp. and Pongamia sp. Int J Env Sci Technol 16:5707–5724

Rao SBN, Kumar DD (2015) Effect of substitution of soybean meal by detoxified karanja cake on diet digestibility, growth, carcass and meat traits of sheep. Small Ruminant Res 126:26–33

Rao RR, Tiwari AK, Reddy PP, Babu KS, Ali AZ, Madhusudana K, Rao JM (2009) New furanoflavanoids, intestinal a-glucosidase inhibitory and free-radical (DPPH) scavenging, activity from antihyperglycemic root extract of *Derris indica* (Lam.). Bioorg Med Chem 17:5170–5175

Rasool U, Hemalatha S (2016) A review on bioenergy and biofuels: sources and their production. Braz J Biol Sci 3(5):3–22

Robak K, Balcerek M (2018) Review of second generation bioethanol production from residual biomass. Food Technol Biotech 56:174

Sahayaraj K, Madasamy M, Anbu Radhika S (2016) Insecticidal activity of bio-silver and gold nanoparticles against *Pericallia ricini* Fab. (Lepidaptera: Archidae). J Biopestic 9:63–72

Saini P, Lakshmayya L, Bisht VS (2017) Anti-Alzheimer activity of isolated karanjin from *Pongamia pinnata* (L.) pierre and embelin from *Embelia ribes*. Burm F Ayu 38:76–81

Sajid ZI, Anwar F, Shabir G, Rasul G, Alkharfy KM, Gilani AH (2012) Antioxidant, antimicrobial properties and phenolics of different solvent extracts from bark, leaves and seeds of *Pongamia pinnata* (L.) Pierre. Molecules 17:3917–3932

Sangeetha R, Geetha A, Arulpandi I (2011) *Pongamia pinnata* seed cake: a promising and inexpensive substrate for production of protease and lipase from *Bacillus pumilus* SG2 on solid-state fermentation. Ind J Biochem Biophys 48:435–439

Sangwan S, Rao DV, Sharma RA (2010) A review on *Pongamia pinnata* (L.) Pierre: a great versatile leguminous plant. Nat Sci 8(11):130–139

Satish PVV, Sunita K (2017) Antimalarial efficacy of *Pongamia pinnata* (L) Pierre against *Plasmodium falciparum* (3D7 strain) and *Plasmodium berghei* (ANKA). BMC Complement Altern Med 17:458

Sharma P, Joshi A, Sharma AK, Dwivedi KN (2013a) Phytochemical and pharmacogostical studty of Karnaja (*Pongamia pinnata* Linn.) Seed. Int J Pharm Res Sci 2:323–332

Sharma S, Verma M, Sharma A (2013b) Utilization of non edible oil seed cakes as substrate for growth of *Paecilomyces lilacinus* and as biopesticide against termites. Waste Biomass Valoris 4(2):325–330

Sharma A, Sharma S, Mittal A, Naik SN (2014a) Statistical optimization of growth media for *Paecilomyces lilacinus* 6029 using non-edible oil cakes. Ann Microbiol 64(2):515–520

Sharma A, Sharma S, Yadav S, Naik SN (2014b) Role of Karanja deoiled cake based medium in production of protease and fatty acids by *Paecilomyces lilacinus* 6029. J Biosci Bioeng 118(3):270–271

Sharmada N, Punja A, Shetty SS, Shet VB, Goveas LC, Rao CV (2016) Optimization of pre-treatment of de-oiled oil seed cake for release of reducing sugars by response surface methodology. Bioethanol 2(1):94–102

Sikarwar MS, Patil MB (2010) Antidiabetic activity of *Pongamia pinnata* leaf extracts in alloxan-induced diabetic rats. Int J Ayurveda Res 1:199–204

Singh R (2007) Insecticidal potential of *Pongamia pinnata* seed fractions of methanol extract against *Earias vitella* (Lepidoptera: Noctuidae). Entomol Gen 30:51–62

Singh R, Kumar A, Tomer A (2015) De-oiled cakes of Neem, Jatropha, Mahua and Karanja: a new substrate for mass multiplication of *T. harzianum*. J Plant Pathol Microb 6(288):2

Sivaramakrishnan S, Gangadharan D (2009) Edible oil cakes.In: Singh-Nee Nigam P, Pandey A (eds) Biotechnology for agro-industrial residues utilisation. Springer, Dordrecht, pp 253–271

Song XD, Xue XY, Chen DZ, He PJ, Dai XH (2014) Application of biochar from sewage sludge to plant cultivation: influence of pyrolysis temperature and biochar-to-soil ratio on yield and heavy metal accumulation. Chemosphere 109:213–220

Soongprasit K, Sricharoenchaikul V, Atong D (2017) Catalytic fast pyrolysis of *Millettia* (*Pongamia*) *pinnata* waste using zeolite Y. J Anal App Pyrolysis 124:696–703

Soren NM, Sastry VRB (2009) Replacement of soybean meal with processed karanj (*Pongamia glabra*) cake on the balances of karanjin and nutrients, as well as microbial protein synthesis in growing lamb. Anim Feed Sci Technol 149:16–29

Soren NM, Sharma AK, Sastry R (2017) Biochemical and histopathological changes in sheep fed different detoxified karanj (*Pongamia glabra*) seed cake as partial protein supplements. Anim Nutri 3(2):164–170

Swamy HMV, Patel NL, Gadad PC, Koti BC, Patel UM, Thippeswamy AHM, Manjula DV (2013) Neuroprotective activity of *Pongamia pinnata* in monosodium glutamate-induced neurotoxicity in rats. Indian J Pharm Sci 75(6):657–663

Takase M, Zhao T, Zhang M, Chen Y, Liu H, Yang L, Wu X (2015) An expatriate review of neem, jatropha, rubber and karanja as multipurpose non-edible biodiesel resources and comparison of their fuel, engine and emission properties. Renew Sustain Energy Rev 43:495–520

Tamrakar AK, Yadav PP, Tiwari P, Maurya R, Srivastava AK (2008) Identification of pongamol and karanjin as lead compounds with antihyperglycemic activity from *Pongamia pinnata* fruits. J Ethnopharmacol 118(3):435–439

Tripathi V, Edrisi SA, Abhilash PC (2016) Towards the coupling of phytoremediation with bioenergy production. Renew Sustain Energy Rev 57:1386–1389

Vadivel V, Biesalski HK (2011) Contribution of phenolic compounds to antioxidant potential and type II diabetes related enzyme inhibition properties of *Pongamia pinnata* L. Pierre seeds. Process Biochem 46:1973–1980

Verma M, Pradhan S, Sharma S, Naik SN, Prasad R (2011) Efficacy of karanjin and phorbol ester fraction against termites (*Odontotermes obesus*). Int Biodeterior Biodegrad 65:877–882

Vinay BJ, Kanya TS (2008) Effect of detoxification on the functional and nutritional quality of proteins of karanja seed meal. Food Chem 106:77–84

Vinodhini J, Malaikozhundan B (2011) Efficacy of neem and pungam based botanical pesticides on sucking pests of cotton. Indian J Agric Res 45:341–345

Vismaya, Belagihally SM, Rajashekhar S, Jayaram VB, Dharmesh SM, Thirumakudalu SKC (2011) Gastroprotective properties of karanjin from karanja (*Pongamia pinnata*) seeds; Role as antioxidant and H^+, K^+-ATPase inhibitor. Evid Based Complement Alternat Med 2011:1–10

Walia S, Saha S, Tripathi V, Sharma KK (2017) Phytochemical biopesticides: some recent developments. Phytochem Rev 16(5):989–1007

Wen R, Lv HN, Jiang Y, Tu PF (2018) Anti-inflammatory flavone and chalcone derivatives from the roots of *Pongamia pinnata* (L.) Pierre. Phytochemistry 149:56–63

Yadav RD, Jain SK, Alok S, Prajapati SK, Verma A (2011) *Pongamia pinnata*: an overview. Int J Pharm Sci Res 2(3):494

Yu X, Li Y, Li Y, Xu C, Cui Y, Xiang Q, Gu Y, Zhao K, Zhang X, Penttinen P, Chen Q (2017) *Pongamia pinnata* inoculated with *Bradyrhizobium liaoningense* PZHK1 shows potential for phytoremediation of mine tailings. Appl Microbiol Biotech 101(4):1739–1751

Zhu L, Lei H, Zhang Y, Zhang X, Bu Q, Wei Y (2018) A review of biochar derived from pyrolysis and its application in biofuel production. SF J Mater Chem Eng 1:1007