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Secondary metabolites: harvesting short term benefits from arid zone agroforestry systems in India

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Abstract Long rotation period of trees and complex trading procedures of wood, are major impediments in spread of agroforestry. Thus, alternative for providing early return to farmers along with long term benefits of raising trees on their farmlands are necessary. Generally, ~ 25% of the trees can be used as timber while the other parts viz. bark, leaves, roots, branches etc. have limited use and are often burnt. In process, leakage of C sequestration potential of trees is reduced. But, tree twigs and leaves can be the potential source of bioactive compounds or secondary metabolites especially in arid region. Vegetation in arid regions possesses very special and unique chemicals which help them to adapt to prevailing harsh conditions. Water stress in these vegetation leads to production of high quantity of reactive oxygen species (ROS) which through a series of pathways eventually leads to higher production of certain special secondary compounds. These compounds, in nature improve defense mechanism of trees, but also have immense pharmaceutical, food, cosmeceutical, nutraceutical and agrochemicals value. They are locally used as folklore medicine but their commercial exploitation can provide short term benefits to farmers. Also, unlike bole, which can be exploited only once, these benefits from trees can be exploited many times during their growing period. Therefore, in this article research work on important secondary metabolites produced by major agroforestry systems of arid region of India has been reviewed along with their industrial applications.

Keywords Secondary metabolites · Agroforestry · Arid zone · Industrial application

Introduction

Practising agriculture solely cannot be a sustainable option in the harsh and drought prone conditions of arid zone. Thus, raising trees along with crops on farmlands is a traditional practice in arid zones worldwide. Trees as a source of food, fodder and fuel provide security to local inhabitants during the drought years and thus are integral part of agriculture (Roy 2018). Even-though farmers of the region are well aware of their utility, introduction of trees in farms, as a component of agroforestry, has met with limited success. There are two reasons for it (1) farmers are benefited after a long gestation period (2) complex legal procedures and fluctuating market prices for trading major tree products (Chavan et al. 2015). This trend can be reversed only if gestation

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period from planting to income from trees could be reduced and income could be generated at regular intervals. Therefore, major challenge for expanding agroforestry lies in finding an alternative option for consistent income generation. Forestry commission of UK estimated that only 25% biomass of the felled trees is converted into timber and rest non-timber products viz. roots, bark, leaves, branches remain largely unused. These under exploited parts of trees could be rich source of secondary metabolites which can be used to develop potential novel products (Forestry Commission 2001; Tyskiewicz et al. 2019) in pharmaceutical, food and flavours, agrochemicals and insecticides industries (Joana-Chavez et al. 2013).

Arid zones are rich in perennial vegetation diversity. Plants in arid areas have distinguished characteristics to survive in harsh environmental conditions. It is due to the presence of secondary metabolites in higher quantity, some of which are specific to endemic vegetation (Croteau et al. 2000; Harlev et al. 2012).Water stress leads to higher production of reactive oxygen species (ROS) (Kleinwachter and Selmar 2015). As a result efficient anti-oxidation defense systems get triggered leading to higher production of secondary metabolites (Wang et al. 2007; Harlev et al. 2012).

Besides imparting tolerance against abiotic stresses (Ahmed et al. 2015), secondary metabolites helps in pollination and also in defense against various pathogens. Carotenoids and flavonoids (Cheynier et al. 2013; Stevenson et al. 2017), terpenes and benzoides (Maia et al. 2013; Paulo et al. 2017; Hetherington-Rauth and Ramirez 2016; Hattan et al. 2016) add pigments to different parts of plants and attract various pollinators. Tannins can defend leaves against insect herbivores by deterrence and/or toxicity (Raymond and Constabel 2011). Phenols and tannins are carbon based secondary metabolites and are believed as chief barricade against the herbivores in woody plants (Chacon and Armesto 2006). Furthermore, secondary metabolites are also used by plants to defend against biotic stresses by production of toxins and antibiotics (Shikano 2017; Ahmed et al. 2015; Cheynier et al. 2013) (Fig. 1).

With all these aspects this paper reviews the important bioactive compounds from arid zone trees and how their integration into medicinal agroforestry will be feasible and profitable stating the commercial application, challenges and future prospects in production of secondary metabolites.

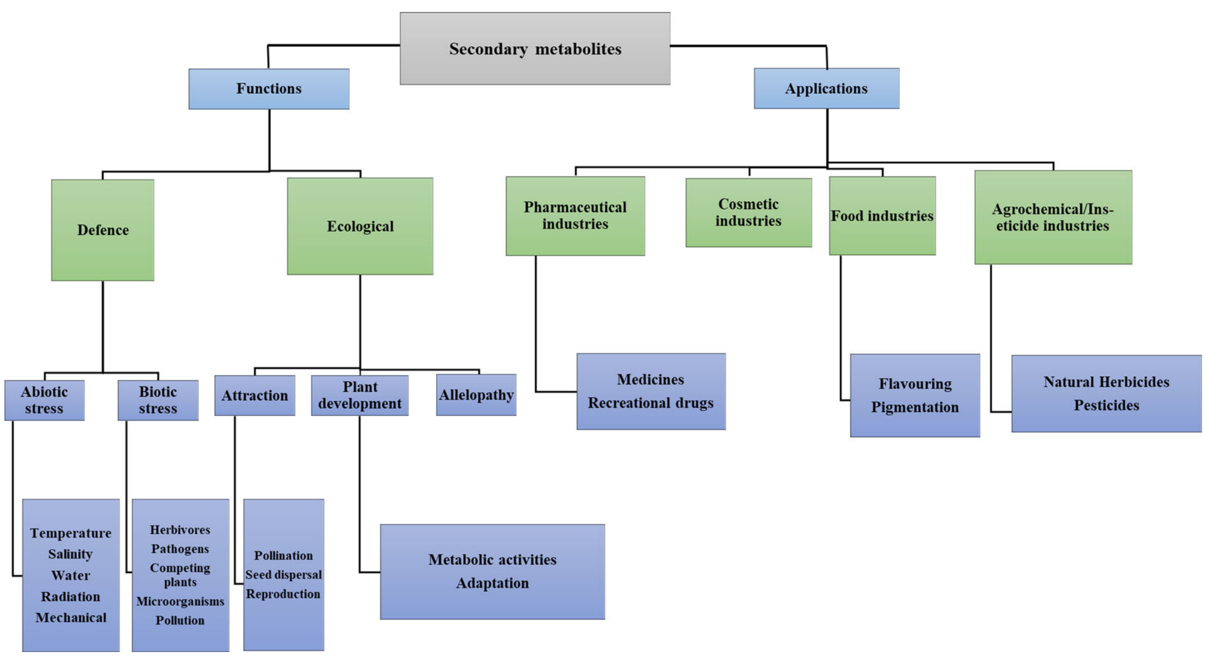

Fig. 1 Functions and applications of secondary metabolites

Secondary metabolite production in arid zone tree species: their bioactive compounds and potential uses

Trees produce range of bioactive compounds like flavanoids, phenols, alkaloids, terpenes carotenoids, resin acids, sugars, sterols, fats, tannins, gums, waxes and suberins. Plant defense metabolites arise from the main secondary metabolic routes, the phenyl-propanoid, the isoprenoid and the alkaloid pathways. The biosynthesis pathway leading to the production of different secondary metabolites is depicted in Fig. 2. The concentration of these bioactive compounds differ from species to species (Coley et al. 2018), among phenotypes/population (Pardo et al. 2018), season to season (Chaves et al. 2013; Ramirez-Briones et al. 2017) and also within the different parts of the tree viz. leaves, branches, heartwood, bark and wounded tissues (Chatha et al. 2014; Wakawa et al. 2018). Secondary metabolites can be divided into four distinct groups: polyphenols, terpenes, nitrogen and sulphur-containing compounds and sugar polymers. The bioactive compounds in different parts of major trees of Western arid Rajasthan are given in Fig. 3.

Polyphenols

Phenolics are comprised of range of compounds varying from flavonoids, anthocyanins, phenolic acids (soluble compounds) to tannins, lignins and cell-wall bound hydroxycinammic acids (non-soluble compounds) (Zhang et al. 2018). These phenolics occur in the form of polymers, acids, or glycosylated esters in trees and perform numerous kind of functions (Arruda et al. 2018). The antioxidants in phenolic compounds of desert plants provide the resistance to

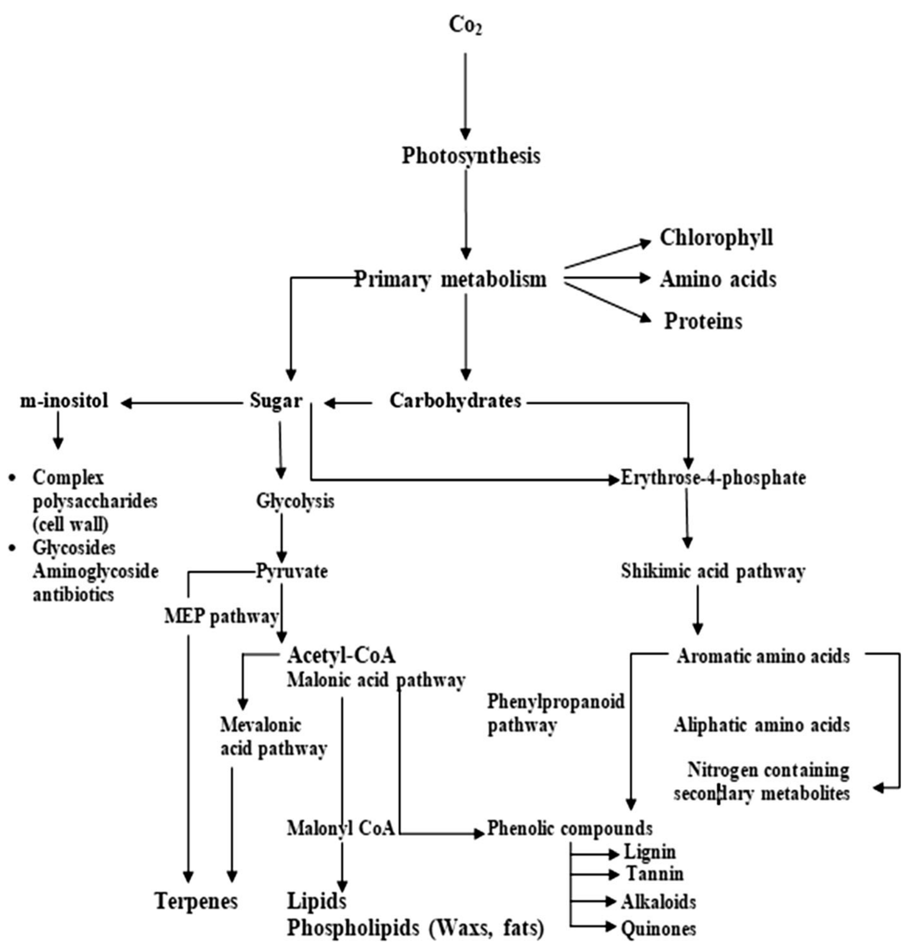

Fig. 2 Biosynthetic pathway for synthesis of secondary metabolites

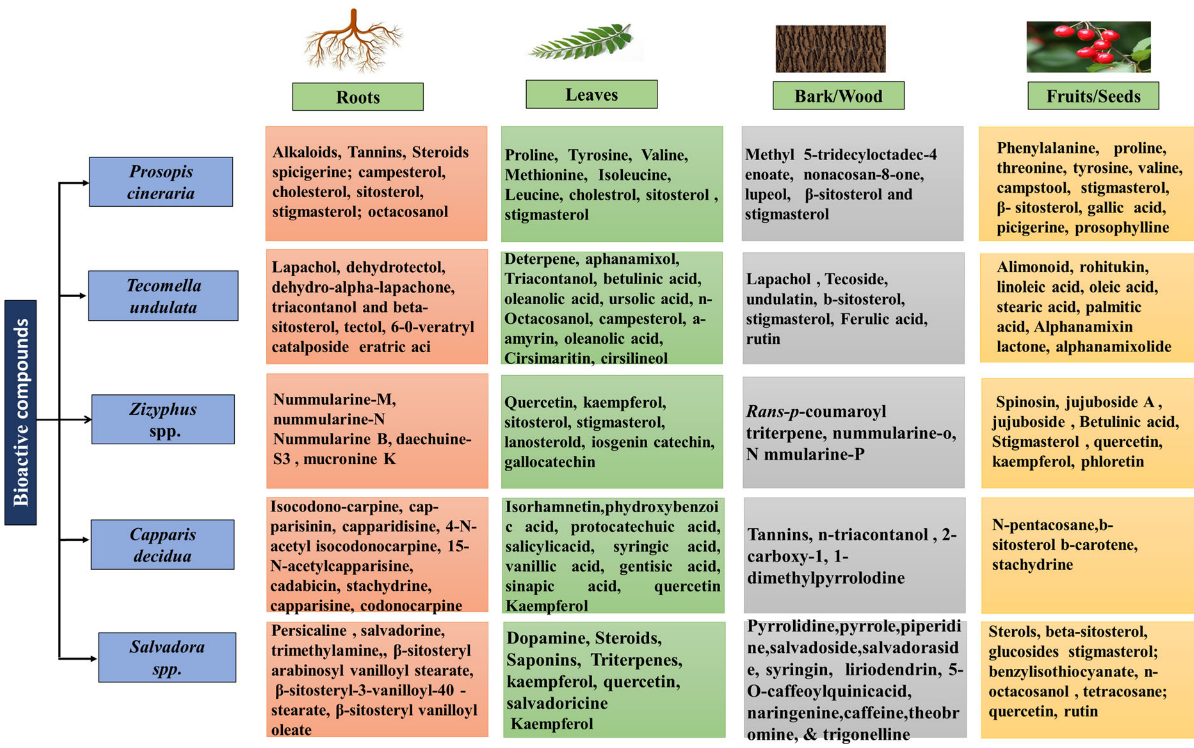

Fig. 3 Bioactive compounds present in various parts of important arid zone tree species of Western arid Rajasthan

severe abiotic stress by reducing ROS and to avoid cell damage (Agati and Tattini 2010; Varela et al. 2016).

Flavonoids

Flavonoids are one of the largest class of secondary metabolites having more than 10,000 structure found in various plant parts like fruits, grains, flowers, leaves, roots, tea and wine. These natural products have several biological functions viz. photoprotection, signaling molecules, pigmentation of flowers, transport of auxin and male fertility (Agati and Tattini 2010; Mathesius 2018). Flavonoid biosynthetic pathways are responsible for resilience in arid zone vegetation under UV-B radiation, drought and salinity stress (Liu et al. 2013; Varela et al. 2016). Metabolomics of arid plants is now receiving increased attention but phenolic compounds and biological activities relationships is still poorly reported for many species of desert ecosystems (Benabderrahim et al. 2019). Some of the species with promising composition of natural antioxidant phytochemicals pertaining to arid ecosystems of India are discussed here.

Tecomella undulata is a pharmaceutically important tree of arid zone having valuable medicinal properties. The aqueous ethanol fractions of leaves and flowers have rich content of flavanoids with prominent antioxidant properties. These compounds have prolific scope in pharmaceutical industries (Laghari et al. 2013). A variety of flavanoids are identified from flower and leaves of this species like quercetin, luteolin7-glucoside, Cirsimaritin, Cirsilineol, Rutin, flavanone, Tiliroside, Genistein, 4′, 7-O-diglucosidemethylmalonylated (Azam and Ghanim 2000; Laghari et al. 2013). The bark of *T. undulata* has antiproliferative properties and the bioactive extract of bark was determined to possess quercetin which could be a potent anti-tumor agent (Ravi et al. 2011). Other arid species also contain substantial amount of flavanoides. *P. cineraria* flowers had highest concentration of flavanoids followed by pods, seeds and leaves (Khandelwal et al. 2016). Presence of flavnoids in leaves, flowers and pods with antioxidant properties is also reported by other workers (Tarachand et al.

2012; Robertson and Narayanan 2014; Pareek et al. 2015).

Presence of flavanoides is also reported in other important species of arid zone like *Capparis deciduas* (Nazar et al. 2018), *Zizyphus* spp. (Kapoor and Mishra 2013; Koley et al. 2011), *Acacia senegal* (Sharma and Kaur 2017), *Cordia myxa* (Malik and Ahmad 2015; Murthy et al. 2019), *Salvadora* spp (Ebrahim and Mekonnen 2018) and *Azadirachta indica* (Al-Jadidi and Hossain 2016).

Tannins

A large number of arid and semi-arid zone species yield tannin in commercial quantities of which some of the important species having potential for extraction are discussed here. Tannins occurring in the bark of *P. cineraria* have antibacterial and antithelmitic properties (Pareek et al. 2015). The bark of *T. undulata* upon phytochemical analysis revealed that it is a rich source of tannins (Dhir and Shekhawat 2012) and in another study species were reported to have 7.14% tannin in seeds (Rohilla and Garg 2014). The presence of tannins in the bark (Jain et al. 2012b), fruits (Rathore et al. 2012; Okala et al. 2014), leaves (Najafi 2013) was also reported in *Zizyphus* species. Phytochemical and antimicrobial screening of *C. decidua* revealed the presence of tannins in the branches along with other phytochemical constituents (Nour and El-imam 2013). Elgailani and Ishak (2014) determined the content of tannins in the bark of *A. senegal* to the tune of 3.49%. The total tannin content estimated in the leaves of *A. indica* was 1.83% (Pandey et al. 2014). The presence of tannins during biochemical screening of the crude extracts of neem leaves was also reported by other workers (Al-Hashemi and Hossain 2016; Ramadass and Subramanian 2018).

Terpenes

Terpenes have larger implication in the industrial sector as flavors, fragrances, spices, perfumery and cosmetics. In the fruits extracts of *Prosopis juliflora* the major compounds identified were terpenoids viz. Limonene diol, Dihydrocarvone, Limonene dioxide, trans Carveol and Dinorsesquiterpenoid. The terpenoidal glycosides in the plant material of *C. decidua* have anticancerous activity. Different terpenoids present in the root bark and stem of this plant has potential for treatment of cancer (Nazar et al. 2018). Terpenoids are one of the major secondary metabolite present in *A. indica*. The dihydromyrcenol, α and β-Pinene, limonene, Myrcene, Camphene (monoterpenoids), Podacarpanoids and beitanoid (di-terpenoids), β-amyrin (Triterpenoids) and β-farnesene, Caryophyllene, Germacrene B, Valencene andα-Himachalen are the various terpenes present in *A. indica* (Kumar et al. 2014). Two new terpenoid compounds ceanothane-type triterpene and one new sesquiterpene along with two known triterpenes were isolated from the fruits of *Z. jujube* (Guo et al. 2009). Phytochemical analysis of *P. cineraria* leaf extract showed the presence of terpenoids in high concentration (Kulshreshtha et al. 2019) as well as pods of *P. cineraria* exhibited the presence of triterpenoids viz. maslinicacid-3 glucoside and linoleic acid with antioxidant activity (Liu et al. 2012).

Carotenoids

In desert conditions carotenoids helps in maintaining balance between photosynthetically active radiation (PAR) (source of energy) and the surplus of light, absence of which may lead to production of reactive oxygen species. Carotenoids thus help in photo-protection, membrane stabilization and photosynthesis (Vitek et al. 2017). The demand for carotenoids global market is expected to reach USD 2.19 Billion by 2026 (Reports and Data, 2019).

The range of carotenoids in 40 genotypes of *P. cineraria* varied from 1.54 to 3.47 mg L^{-1} (Manga and Sen 2001). Ripe fruit of *C. decidua* contains 14% of β-carotene which is adequate to fulfil the requirement of vitamin A. Flowers and fruits also exhibited the presence of β-carotene (Mishra et al. 2007). The dried pods of *P. cineraria* procured from market consist of 9.89 mg β-carotene 100 g^{-1} (Chaturvedi and Nagar 2001). The amounts of carotenes in *Z. jujuba* fruits were ranging between 4.12 and 5.98 mg 100 g^{-1} on a dry weight basis. Similarly, ripened fruit of *S. persica* contains considerable amount of carotenoids ranging between 9.03 and 13.98 µg 100 g^{-1} dry weight. Fruits of *S. persica* are good quality food supplements for intake of carotenoids (Kumari et al. 2017). The content of total carotenoids in *A. indica* tree reported was 366.38 mg 100 g^{-1} on fresh weight basis (Taha et al. 2017). Afzal et al. (2004) isolated eight carotenoids from leaves of

Cordia myxa. The major carotenoid present in leaf extract was Lutein followed by violaxanthin and β-carotene.

Nitrogenous secondary metabolites

Bioactive nitrogenous compounds include alkaloids, cyanogenic glucosides, and non-proteins amino-acids which are mostly biosynthesized from amino acids (Pagare et al. 2015).

Alkaloids

Alkaloids are basic compounds derived from amino acids that contain one or more heterocyclic nitrogen atom and are classified according to the type of ring (pyrrolidine, piperidine etc.) and their biosynthetic origin (Khan et al. 2013). Alkaloids have immense pharmaceutical applications and their commercial significance has increased in recent years (Khan et al. 2013). The accumulation of natural products is more under drought stress condition as compare to well irrigated conditions and thus the concentrations of nitrogen-containing substances, such as alkaloids are also positively influenced by drought stress conditions (Kleinwachter and Selmar 2015).

In arid zone species like *P. cineraria* phytochemical screening revealed the presence of alkaloids in leaves, flowers, pods and seeds (Khandelwal et al. 2016). A compound was isolated from *P. cineraria* which is known to be analogue of piperidine alkaloid showing the highest lipid peroxidation (LPO) and cyclooxygenas (COX) enzyme inhibitory activities. These enzyme inhibitory activities support the certainty of *P. cineraria* pods possessing functional food properties (Liu et al. 2012). The isolation of alkaloids like Spicigerine and Prosophylline is reported from the plant (Garg and Mittal 2013).The presence of alkaloids in *P. cineraria* is also reported by several other workers (Tarachand et al. 2012; Agrawal et al. 2019). *T. undulata* tree is reported to be very rich in alkaloids and total of eleven (11) structurally diverse alkaloids were identified from the flowers. A qualitative phytochemical analysis showed the presence of alkaloids in leaf and bark extracts of *T. undulata*, therefore leaf and stem bark extracts can be used in synthesis of herbal as well as synthetic drugs and as antifungal agents for crop protection as well (Parveen and Sharma 2014). Phytochemical analysis of dried fruits of *C. decidua* and seeds of *A. senegal* revealed the presence of alkaloids which may be responsible for the antimicrobial properties of these plants (Sharma and Kaur 2017).

The phytochemical screening of *A. senegal* stem revealed alkaloids are present in the tree stem in varying amounts (Suleiman et al. 2017). *C. decidua* has many pharmacological activities which can be ascribed to the presence of array of alkaloids like capparisinine, capparisine, stachydrine, isocodonocarpine (Nazar et al. 2018). Some other alkaloids isolated from *C. decidua* capparisinine with antimicrobial properties (Ahmad et al. 1985; Upadhyay 2011) and capparidisine (Ahmad et al. 1992) cadabicine, stachydrine and codonocarpine with anticancerous properties (Ahmad et al. 1992; Upadhyay 2011). A new sulphur-containing imidazoline alkaloid 1,3-Dibenzyl-4-(1,2,3,4-tetrahydroxy-butyl)-1,3-dihydroimidazole-2-thione, persicaline was isolated from roots of *S. persica* possessing reasonable antioxidant activity (Farag et al. 2018). The roots (Swamy and Timothy 2015), twigs and stem (Boshra et al. 2016) of *S. persica* also show the presence of alkaloids. There are number of cyclopeptide alkaloids isolated from root bark of *Z. nummularia* viz. nummularine-M, nummularine-N, whereas nummularine-o, Nummularine-P and mauritine-D (peptide alkaloid) were isolated from stem bark (Dwivedi and Pandey 1987). The GC analysis of *C. myxa* fruits revealed the presence of 10 alkaloids with one major component comprising about 64% of the total extract (Shwaish and Al-Imarah 2016).

Sugar polymers

The nonstructural carbohydrates (NSC) like sugars and starch mainly involve in primary and secondary metabolism. Trees are not majorly exploited for the sources of starch however non-structural polysaccharides in gums are utilized in food, pharmaceutical industries as binding agents in paints and varnishes. These gums are not food reserves, but usually ooze in response to any injury done to plants composed of terpenes and other compounds (Obst 1997). The major source of gum (Gum Arabic) exploited in arid regions of India is from *Acacia senegal*. Gum Arabic is a natural branched-chain polysaccharide of 1,3-linked β-D-galactopyranosyl with side chains linked to the main chain by 1,6-linkages units. Both the mainand the side chains contain units of α-L-arabinofuranos, α-L-rhamnopyranosyl, β-D-glucopyranosyl, and 4-O-methyl-β-D-glucopyranosyl, the last two mostly as end units (Musa et al.2019).

Gum Arabic is used as stabilizer, a thickener, emulsifier and binding agent in several food industries owing to its excellent emulsifying properties and low solution viscosity. In food industry its chiefly used in confectionery, bakery, beverages and as a microencapsulating agent. It has important role in traditional medicine system also. In arid regions of India it is used for preparation of a sweet which is given to pregnant mothers as it is rich in calcium and protein. It improves immunity and if had during winter will prevent from cold and cough (Shiran et al. 2018). It is also used in veterinary medicine to treat skin diseases. ICAR-Central Arid Zone Research Institute (CAZRI), Jodhpur identified other edible gum producing tree species in hot arid region which includes *Acacia jacquemontii*, *A. tortilis*, *A. nilotica*, *Anogeissus pendula*, *A. rotundifolia* and *Prosopis cineraria*.

Arid zone agroforestry systems as a source of secondary metabolites

Trees in arid zones provide every essential item used in each household i.e. food, fuel, fodder, timber and even medicines. Thus, raising and retaining of trees on agricultural lands is a custom practise so as to avoid the risk of failure during drought. As discussed above most of the arid zone trees have immemse pharmaceutical properties attributable to wide range of bioctive compounds present. The extraction of these bioactive compounds is mainly done from forests, natural woodlands and long term fallow lands which is threatening the existence of certain valuable species. Therefore, it is required to raise these tree and crop species outside forests which will meet the demand of pharmaceutical industries besides conserving genetic diversity (Rao et al. 2004; Thakur et al. 2020). However, scientific information available on the performance of different medicinal plants and trees while integrating in agroforestry system under hot arid conditions is limited (Arya 2003). Future, research work needs to identify medicinal tree crop combinations with maximum economic profitability viz a viz. developing relevant management practices for same.

i) Tree species with medicinal values grown in traditional arid zone agroforestry systems

Trees grown in traditional agroforestry system of Rajasthan viz. *P. cineraria*, *T. undulata*, *A. senegal*, *Zizyphus* spp., *C. decidua*, *Salvadora* spp. etc. have rich medicinal properties. These medicinal trees can be grown as shade providers, as boundary fencing or on soil conservation structures. Medicinal tree species that grow tall and develop open crown at the top can be used for this purpose (Rao et al. 2004). *P. cineraria* known as wonder tree of desert have antibacterial, antihyperglycemic, antihyperlipidemic and antioxidant activity. Moreover, the tree is highly suitable for agroforestry purposes as it does not compete with the associated agricultural crops nor its growth is affected by the intercrops (Gupta et al. 1998; Kumar et al. 2018). Likewise, *T. undulata* is known for its valuable medicinal properties in both folk and classical streams of indigenous medicinal systems having wide range of therapeutic activities. Due to survival even in extreme conditions, it is widely accepted tree species in arid zone agroforestry. The species thrives very well on stabilized sand dunes, which experience extreme low and high temperatures (Kalia et al. 2014). Another important genus of arid zone is Ziziphus utilized not only for food but also play a multiple role in dry zone agro forestry systems. Different parts of tree have variety of medicinal uses to treat the several ailments locally (Singh and Meghwal 2020). Some example of medicinal tree crop integrations in arid regions of India are given in Table 1.

ii) Medicinal plants as intercrops

Cassia angustifolia (Senna), *Aloe barbadensis* (Aloevera), *Plantago ovata* (Isabgol), *Withania somnifera* (Ashwagandha) *Citrullus colocynthis* (tumba), *Datura spp* (Dhatura), *Lawsonia inermis* (mehandi), *Commiphora wightii* (gugal), *Ricinus communis* (castor), *Evolvulous alsinoides* (shankhpushpi) etc. are promising medicinal plants for commercial scale cultivation in region. These crops can be incorporated into medicinal agroforestry systems where trees may allow intercropping depending on the spacing and nature of the trees. During the establishment phase trees does not compete with crops and crops give maximum output in intial years. Though, the competition rise during later stages but economic analysis shows that

Table 1 Some examples of medicinal tree crop integrations in arid zone agroforestry systems

Tree species	Medicinal intercrop	Remarks	References
Prosopis cineraria	*Cassia angustifolia*	Growth and dry leaf yield of *C. aungustifolia* leaves was enhanced	Vyas (2001)
Zizyphus mauritiana	*Aloe barbadensis*	The growth and yield of *Z. mauritiana* was more with *A. barbadensis*	Saroj et al. (2003)
Ailanthus excelsa, Acacia nilotica, Colophospermum mopane	*Cassia aungustifolia*	High yield of *C. aungustifolia* is achievable when combined with *A. nilotica* and *A. excelsa* in silvi-herbal practices	Arya (2003)
Emblica ofiicinalis	*Withania somnifera*	*W. somnifera* performance was best under sole cropping followed by *E. ofiicinalis*	Madhavi (2011)
Zizyphus mauritiana	*Cassia aungustifolia*	Growing of intercrops between the alleys of ber significantly influenced the productivity of ber	Singh et al. (2018)

integrated medicinal agroforestry systems provide more economic benefit as compare to monocropping (Kumar et al. 2015a; Thakur et al. 2017, 2020). Trees also benefit from the inputs and management given to the intercrops. Medicinal and aromatic crops are more remunerative compared to traditionally grown annual crops if market opputunities are well established (Rao et al. 2004). Brief reveiw of profitability of growing medicinal crops as intercrops in arid zone agroforestry systems is given in Table 2.

Secondary metabolites: potential for commercial use

Important well-known tree-derived natural products include: drugs quinine (the antimalarial alkaloid derived from Cinchona bark, industrial raw materials such as fatty acids, pine oil, and natural rubber (Balandrin and Klocke 1988). These days the demand for natural compounds is rising in functional food industries also. Bioactive compounds have actions in the body that may promote good health. They are being studied in the prevention of cancer, heart and

Table 2 Brief review of profitability (Rs./ha) of medicinal plants based arid agroforestry systems

Tree crop combination	Net return (× 10^3 Rs./ha)			Total net returns (× 10^3 Rs./ha) or B:C ratio	Reference
	Sole crop	Sole tree	Agroforestry sytem		
Zizyphus mauritiana + *Cymbopogon martinii*	8.57	6.71	9.80	25.08	Ismail and Reddy (2004)
Zizyphus mauritiana + *Aloe barbadensis*	–	–	65.80	65.80	Dhandar et al. (2004)
Zizyphus mauritiana + *C. flexuosus*	14.41	6.71	15.80	36.92	Ismail and Reddy (2004)
Emblica officinalis + *Andrographis paniculata*	34.80	–	59.31	2.01	Madhavi (2011)
Emblica ofiicinalis + *Withania sominfera*	17.52	–	24.40	0.85	Madhavi (2011)
Zizyphus mauritiana + *Cassia aungustifolia*	–	57.22	29.79	87.01	Singh et al. (2018)

other diseases (Lavanya 2015). Bioactive compounds produced by some important arid zone species, its function and industrial application is shown in Table 3.

Pharmaceutical applications

Medicine and remedies for some of incurable and deadly diseases like AIDS (Acquired immunodeficiency syndrome) can be found in plants in some new form we never knew. Therefore, the secondary metabolites some known and some new from the arid zone tree species will represent interesting library with hidden therapeutic potentialities can be used directly or along with synthetic modern medicine. Now-a-days there is much focus on using herbal and natural remedies which evidently increased the market for natural plant products (Ekor 2014; Welz et al. 2018). Salicin from genera Salix, Populus and Taxol from the Yew tree are excellent examples in this context (Rungsung et al. 2015).

Food industries

For eradication of pathogens and spoilage microorganisms currently food industries are preferring natural plant products which are eco friendly and satisfying the consumer demand for greener products. Therefore, food preservatives with natural antimicrobial and antioxidant properties are focused upon as they delay the oxidation of biomolecules and increase the shelf lives of food products (Bondi et al. 2017; Lourenco et al. 2019). Pomegranate is one of the example of arid zone fruit which is tremendously rich in antioxidants. The production of these active barriers with natural biopolymers has received increasing attention as an alternative to synthetic, non-biodegradable plastic packaging or biofilms (Lourenco et al. 2019; Ali et al. 2018).

Agrochemicals

The use of plant extracts as pesticides on field as well as during post harvest period is gaining interest because of distinguished problems with chemical pesticides like genetic resistance to pests, toxic residues in products, environmental and human health hazards etc. (Adeyemi 2010; Kortbeek et al. 2019). Azadirachtin from neem trees are long used in agriculture to control insect pests (Adeyemi 2010; Benelli et al. 2017). Though, the scientific research to explore the parts of trees along with the active compounds having toxicity against insects and pathogens is limited.

Cosmeceuticals

Bioactive compounds from natural extracts of plants are also effectively employed in various skin care applications (Dorni et al. 2017). Number of plants are used in novel cosmeceutical formulations for their role in anti-ageing, anti-allergic, antioxidants, anti-wrinkling and as protection against sun rays (Radice et al. 2016; Dorni et al. 2017). There is need to study the trees of cosmeceutical importance and the scientific evidence for their commercial value (Ribeiro et al. 2015).

Challenges in production of secondary metabolites

Latest advancement in technology and research indicate that natural compounds will be dominating the market in future (Atanasov et al. 2015). However, there are certain challenges associated with the production and processing of these natural bioactive compounds to be addressed for their large scale utilization. Production cost, scalability, bioprocessing technology, development of the markets and supply chain are major challenges to prevail over.

Production cost

Foremost challenge is the identification of bioactive compounds with available amount of plant material. Small quantity is required only for initial pharmacological evaluation, though afterwards a larger quantity of plant material is required for thorough categorization of different constituents. Furthermore, this small quantity becomes constraint when plant has some important active ingredient which becomes the essential part of some industrial product (Lam 2007; Atanasov et al. 2015). Higher level production of metabolites is hindered by basic knowledge on the their biosynthesis, transport and accumulation (Kumar et al. 2015b). Moreover, the huge and indiscriminate collection of plant material for extraction of bioactive compounds has threatened the survival of some species. Therefore, production of these compounds

Table 3 List of bioactive compounds produced by some important arid zone tree species, their function and industrial application

Sl. no	Species	Plant part	Bioactive compounds	Function	Industrial application	References
1	*Prosopis cineraria*	Leaves	Quercetin	Anicancerous, antioxidant, antimicrobial	Pharmaceutical, food packaging	Robertson and Narayanan (2014)
		Leaves, flowers, seeds	Luteolin, spicigerine	Anicancerous, anti-inflammatory, anti-allergic, neuroprotective	Pharmaceutical	Pareek et al. (2015)
		Leaves, bark, pods	Campesterol, sitosterol, stigmasterol	Antioxidant, reduces the absorption of cholesterol	Pharmaceuticals, functional foods, cosmetic industry	Garg and Mittal (2013), Pareek et al. (2015)
		Flower	Rutin	Antioxidant, anticarcinogenic, neuroprotective cardioprotective, antimicrobial	Pharmaceuticals, herbal medicines, multivitamin preparations, the cosmetic and chemical industries and animal feed	Bishnoi et al. (2018)
2	*Tecomella undulata*	Flowers, leaves	Rutin, quercetin	Antioxidant antiviral, anticancer, antimicrobial, anti-inflammatory	Pharmaceutical, nutraceuticals industry, nanoencapsulation	Dhir and Shekhawat (2012), GaneshPurkar and Saluja (2017)
		Flowers	Luteolin 7-glucoside, Sitosterol	Antidiabetic	Pharmaceutical nutraceutical	Dhir and Shekhawat (2012)
		Leaves	Cirsimaritin, Cirsilineol	Ultraviolet photoprotection, hair color treatments	Cosmetic industries	Azam and Ghanim (2000)
			Triacontanol	Plant growth regulator	Agrochemical	Azam (1999)
			Oleanolic acid,	Anticancer, anti-osteoporosis, anti-obesity, anti-diabetic, lipid-lowering, anti-inflammatory, antioxidant, immune-regulatory and hepatoprotective effects	Pharmaceutical industry	Azam (1999)
			Ursolic acid betulinic acid	Antioxidant, antimicrobial, anti-inflammatory, anti-tumor, chemopreventive, cardioprotective	Cosmetic, cosmeceutical, nutraceutical or pharmaceutical products agrochemical,	Azam (1999), Hordyjewska et al. (2019)
		Heartwood	Radermachol	Anti-inflamatory activity	Pharmaceutical	Singh et al. (2008)
			Stigmasterol	Antiosteoarthritic, antihypercholestrolemic, cytotoxicity, antitumor, hypoglycaemic, antimutagenic, antioxidant, anti-inflammatory and CNS effects	Pharmacological prospects, food additives	Jain et al. (2012a), Kaur et al. (2011)

Table 3 continued

Sl. no	Species	Plant part	Bioactive compounds	Function	Industrial application	References
			β-sitosterol	Anti-inflammatory, antineoplastic, anti-pyretic, and immunomodulating, chemoprotective activities	Nutraceutical and Pharmaceutical industries	Jain et al. (2012a)
			Lapachol, α-lapachone, β -lapachone	Anticancer, antibacterial, antifungal, antivirus, antitumor	Pharmaceutical industries	Jain et al. (2012a)
3	*Zizyphus* spp	Leaves	Quercitrin	Antioxidant antibiofilm bioactivity	Pharmaceutical food industry	Damiano et al. (2017)
		Fruits	Quercetin, kaempferol,	Antioxidant, antiviral, anticancer, antimicrobial, anti-inflammatory	Pharmacologica, nanoencapsulation	Pawlowska et al. (2009)
		Root bark	Nummularine-M, nummularine-N, whereas nummularine-o, Nummularine-P and mauritine-	Antiproliferative, antiplasmodial, antitubercular activity	Pharmaceuticals, biological fertilizers Food industry	Dwivedi and Pandey (1987), Aniszewski (2015)
		Stem bark	Scutianine-C; Scutianine-D; Jubanine-C and Ziziphine-A r	Antiproliferative, antiplasmodial, antitubercular activity	Pharmaceuticals, biological fertilizers Food industry	Tripathi et al. (2001), Aniszewski (2015)
		Fruits, roots	Betulin; betulinic acid	Antimalarial, antiretroviral, anti-inflammatory anti-inflammatory effects, anti-cancer, ovarian cancer, anti- fibrotic effects	Pharmaceutical, cosmeticsperfume, agrochemical, and cosmetic products	Kundu et al. (1989), Hordyjewska et al. (2019)
		Roots	Ursolic acid	Antioxidant, antimicrobial, anti-inflammatory, hepatoprotective, immunomodulatory, anti-tumor, chemopreventive, cardioprotective, anti-hyperlipidemic and hypoglycemic activitie	Cosmetic, cosmeceutical, nutraceutical or pharmaceutical products	Kundu et al. (1989)
4	*Capparis decidua*	Root bark	Spermidine, spermine polyamines Capparisinine, capparidisine, Isocodonocarpine, codonocarpine	Antioxidant, anti-arteriosclerotic, and anti-allergenic, cell proliferative properties properties	Pharmaceutical products, food industry	Ahmad et al. (1992)
		Flowers, seeds	*β*-sitosterol	Anti-inflammatory, antineoplastic, anti-pyretic, and immunomodulating, chemoprotective activities	Nutraceutical and pharmaceutical industries	Ahmad et al. (1987)
		Seeds, fruits	*β*-carotene	Antioxidant	Food and beverages, pharmaceuticals and dietary supplements, cosmetics industry	Ahmad et al. (1987)

Table 3 continued

Sl. no	Species	Plant part	Bioactive compounds	Function	Industrial application	References
		Fruits	isoginkgetin and ginkgetin	Anti-inflammatory activity	Pharmaceutical	Upadhyay (2011)
		Leaves, flowers	Rutin, tocopherol, quercitin	Antiviral, analgesic, anticancer	Pharmaceutical	Upadhyay (2011)
5	*Salvadora spp.*	roots	Salvadorine, trimethylamine, persicaline	Anti-bacterial effects anti-oxidant	Pharmaceutical	Sharma et al. (2018), Farag et al. (2018)
		stem	Salvadoside, salvadoraside, syringin, and liriodendrin	Anti-bacterial effects	Pharmaceutical	Ohtani et al. (1992)
		bark	Caffeine, theobromine, and trigonelline	Hypoglycemic, hypolipidemic, neuroprotective, antimigraine, sedative, memory-improving, antibacterial, antiviral, and anti-tumor activitie	Pharmaceutical productschocolate beverages and in various forms of chocolate-based foods	Aumeeruddya et al. (2017)
		leaves	Salvadoricine	Anti-inflammatory, antimicrobial, anticancer activity	Pharmaceutical industries	Malik et al. (1987)

become very time consuming and costly procedure (Joana-Chavez et al. 2013; Kumar et al. 2019).

Scalability

The other challenge is to describe and understand the diversity of secondary compounds and their modes of action alone or in natural combinations as found in plants (Lam 2007; Ekor 2014; Wink 2015). Besides the availability and accessibility of planting material another important parameter is the quality of the compound isolated. During extraction, as well as during the isolation processes, transformation and degradation of compounds can occur (Atanasov et al. 2015). Plant metabolite pool is influenced by various environmental and seasonal responses involving altered plant gene expressions resulting in temporal or spatial metabolite variations. Further, the presence of particular metabolite in excess cause significant chemical interferences in the method performance. For example, high levels of sugars often interfer with the ability to profile flavonoids in plant extracts. Accelerated Solvent Extraction or Microwave Assisted Extraction in combination with hyphenated techniques such as Gas Chromathography–Mass Spectrometry (GC–MS) and Liquid Chromatography–Mass Spectrometry (LC–MS) performs fast and reproducible analytical methods for the quality control of secondary metabolite production (Bertoli et al. 2010; Roopashree and Naik 2019).

Bioprocess technology

Metabolites have a high demand in various industries but their supply is limited by complex synthesis mechanism, high cost of production and the decreasing availability of raw materials of medicinal plants. The empirical methods including labeled precursor addition, gene cloning, intermediate identification, expressed sequence tag (EST) libraries, enzyme purification and characterization have not been able to meet the increasing world demand for valuable natural products, including the anticancer agent paclitaxel, which reached 1040 kg per year in 2013 according to the Global Industry Analysts. Such techniques are more time consuming and complex to understand (Kumar et al. 2019). Metabolic engineering, transcriptomics, proteomics and functional genomics are some of the biotechnological approaches having potential in the future align with the progress of the knowledge of plant biosynthetic pathways (Joana-

Chavez et al. 2013; Kumar et al. 2019). Administering these kind of novel approaches in a efficient way for production of natural compounds will make possible to increase the competence and discovery of new compounds from available plant material (Lam 2007).

Development of markets and supply chain

Natural herbal products, drugs and medicines are currently prefered for commercialization by entrepreneurs. The domestic trade of the AYUSH industry (Indian medicine system) in India is of the order of Rs. 80 to 90 billion (1US$ = Rs. 50). The Indian medicinal plants and their products also account of exports in the range of Rs. 10 billion. Indian share in the world trade, at present, however, is quite low. The medicinal plants trade is carried out through Mandis involving lot of inetrmediaries and farmers dont have acess to price information and other market trends. Arid areas have rich and diverse market for herbal medicines. The development of the markets and improving value chain by i) reduction in post-harvest losses (ii) Public private partnership for marketing of the produce (iii) Favorable government policies for enhancing the cultivation and value chain of the medicinal herbs (iv) Efficient marketing information system to the producres and other stakeholder involve in value chain (v) Vertical integration of farmers through cooperatives, contract farming and retail chains of medicinal plants growers can ensure sustainable supply to the herbal industry, folk users and growing global markets (Rathore and Mathur 2019).

Arid and semi arid agroforestry plants have high commercial value and demand of their bioactive products but at the same time agroforestry plants in these regions require more inputs to maintain their quality. The challenges associated with the production, extraction and marketability of bioactive compounds from arid zone agroforestry systems and recommendations to overcome these challenges are listed in Table 4.

Future prospects

The demand of herbal medicinal and cosmetic products is increasing because of increased interest of consumers in natural products as they are considered safer and more cost effective than synthetic products.

Table 4 Challenges in production of secondary metabolites from arid zones agroforestry systems with feasible recommendations

Challenges	Recommendations	Feasability and profitability
To enhance the production of metabolites	Elicitation approaches	Biotic elicitor enhanced the production of azadirachtin by approximately fivefold Jasmonic acid and salicylic acid showed a approximately 6 and ninefold enhancement, respectively, in the production of azadirachtin (Satdive et al. 2007)
Diversity of metabolite content among genotypes	Identification and multiplication of genotypes with higher metabolite content	The range of phenolics and flavonoids in 12 commercial genotypes of Indian jujube were evaluated. Ascorbic acid and total phenolics ranged from 19.54 to 99.49 mg/100 g and 172 to328.6 mg GAE/100 g, respectively. Therefore, the cultivars with high antioxidant potential can be used in germplasm breeding programs (Koley et al. 2011)
Empirical bioprocess technologies	Use of modern techniques like Metabolic engineering, transcriptomics, proteomics and functional genomics	The production of guggulsterone a potential bioactive constituent exctracted from *Commiphora wightii* an important gum resin plant of arid region is improved by sugars and morphactin in the cell cultures and by plant gum elicitation (Sharma et al. 2011)
Market accessibility	Post harvest management Grading and cleaning Value addition Export promotion	The value added products from *Emblica officinalis* fruit retains bioactive components even after processing. The sensory scores shows that the processed products are not only good source of antioxidant but also have more consumer acceptance (Puranik et al. 2012)

According to World Health Organization (WHO) about 80% population of most developing countries still rely on traditional herbal medicines for their primary health care needs. Overall international trade in medicinal plants and their products was US$ 60 billion in 2010 and is expected to reach US$ 120 billion by 2024 and US$ 5 trillion by 2050. In Asia, the demand of herbal market had almost doubled during late 1990s due to increase in population. Global Nutraceuticals Market has been projected to rise at over 8.3% per annum to reach US$ 30 billion in 2015. A large number of food and pharmaceutical, nutraceuticals and nutraceuticals companies are active in the field because they consider that this market has promising growth potential.

Conclusions

Trees are mainly raised on farm fields to fulfill the needs of timber, fodder, fuel, food, controlling erosion and desertification and thus bringing sustainability to the production system. Lot of efforts has gone in past 50 years to evolve planned agroforestry as people's movement in arid farm lands. But their slow growth leading to long gestation before their commercial exploitation (25–30 years) has continued to be a major impediment. Farmers need to have returns in short span of time which can be achieved, by addressing a relatively unexplored domain of extraction of secondary metabolites. Vegetation in arid region is rich in unique bioactive compounds. Extraction and evaluation of these constituents from trees along with their application in various industries has been discussed to boost up their utilization and in due course enhance the income of farmers for motivating them to adopt agroforestry. Though, there are certain challenges like identification of bioactive compounds with limited plant material, understanding their diversity and biosynthetic pathways which needs to be overcome using novel approaches.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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