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Genetic resources of *Curcuma*: diversity, characterization and utilization

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Abstract

The genus *Curcuma* (family *Zingiberaceae*) comprising over 80 species of rhizomatous herbs, is endowed with widespread adaptation from sea level to altitude as high as 2000 m in the Western Ghats and Himalayas. Having originated in the Indo-Malayan region, the genus is widely distributed in the tropics of Asia to Africa and Australia. *Curcuma* species exhibit inter- and intra-specific variation for the biologically active principles coupled with morphological variation with respect to the above-ground vegetative and floral characters as well as the below-ground rhizome features besides for curcumin, oleoresin and essential oil. *Curcuma* is gaining importance world over as a potential source of new drug(s) to combat a variety of ailments as the species contain molecules credited with anti-inflammatory, hypocholestraemic, choleratic, antimicrobial, insect repellent, antirheumatic, antifibrotic, antivenomous, antiviral, antidiabetic, antihepatotoxic as well as anticancerous properties. Turmeric oil is also used in aromatherapy and in the perfume industry. Though the traditional Indian Ayurvedic system of medicine and Chinese medicine long ago recognized the medicinal property of turmeric in its crude form, the last few decades have witnessed extensive research interests in the biological activity and pharmacological actions of *Curcuma*, especially the cultivated species. Turmeric powder obtained from rhizomes of *Curcuma longa* or related species is extensively used as a spice, food preservative and colouring material, in religious applications as well as a household remedy for bilary and hepatic disorders, anorexia, diabetic wounds, rheumatism and sinusitis in India, China and South-East Asia and in folk medicine. Cucuminoids, the biologically active principles from *Curcuma*, promise a potential role in the control of rheumatism, carcinogenesis and oxidative stress-related pathogenesis. *Curcuma longa* L. syn. *Curcuma domestica* Val., common turmeric, is the most economically valuable member of the genus having over 150,000 hectares under its cultivation in India. In addition to *Curcuma longa*, the other economically important species of the genus are *C. aromatica*, used in medicine and toiletry articles, *C. kwangsiensis*, *C. ochrorhiza*, *C. pierreana*, *C. zedoaria*, *C. caesia* etc. used in folk medicines of the South-East Asian nations; *C. alismatifolia*, *C. roscoeana* etc. with floricultural importance; *Curcuma amada* used as medicine, and in a variety of culinary preparations, pickles and salads, and *C. zedoaria*, *C. malabarica*, *C. pseudomontana*, *C. montana*, *C. decipiens*, *C. angustifolia*, *C. rubescens*, *C. haritha*, *C. caulina* etc. all used in arrowroot manufacturing. Crop improvement work has been attempted mainly in *C. longa* and to a little extent in *C. amada*. At present there are about 20 improved varieties of *C. longa* in India and one in *C. amada*, evolved through germplasm/clonal selection, mutation breeding or open-pollinated progeny (true turmeric seedlings) selection. Though work on morphological characterization of *Curcuma* species has been attempted, its molecular characterization is in a nascent stage except for some genetic fidelity studies of micropropagated plants and

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isozyme-based characterization. The genus has also been examined from the biochemical profiling and anatomical characterization angle. This article is intended to provide an overview of biological diversity in the genus *Curcuma* from a utilitarian and bio-prospection viewpoint.

Keywords: breeding and varieties; characterization; cultivation and processing; *Curcuma*; economic botany; genetic resources; taxonomy; turmeric

Introduction

The genus *Curcuma* belonging to the family *Zingiberaceae*, considered to have originated in the Indo-Malayan Region (Purseglove, 1968), has a widespread occurrence in the tropics of Asia to Africa and Australia. Out of the 100 or so species reported in the genus, about 40 are of Indian origin (Velayudhan *et al*., 1999).

Turmeric is mainly known as a spice all over the world. The literature is redolent with its use as a spice in curry powder, chicken bouillon, sauces, gravies, dry seasoning, baking mixes, processed cheese pickles, relishes, breading soup, beverages and confections (Sasikumar, 2001). Turmeric is also credited with religious and magical rites in India and certain South-East Asian countries. Some species of *Curcuma* are also recognized for their ornamental value by the floriculture industry. Traditionally, turmeric has been used in India for treatment of a variety of human and veterinary ailments, as a natural dye, as well as in preparation of delicious dishes. Though traditional Indian Ayurvedic and Sidha systems of medicine have recognized the medicinal value of turmeric in its crude form since very ancient times, the last few decades have witnessed extensive research interests worldwide in the biomedical activity of turmeric and its compounds. Thus *Curcuma* is now gaining importance all over the world as a mighty cure to combat a variety of ailments, as the genus carries molecules credited with anti-inflammatory, hypocholestraemic, choleratic, antimicrobial, antirheumatic, antifibrotic, antivenomous, antiviral, antidiabetic, antihepatotoxic and anticancerous properties as well as insect repellent activity (Chattopadhyay *et al*., 2004). A US Patent (No. 20030185907) is now in place on a method of treatment of inflammation and pain in mammals including human beings using curcuminoids along with other plant-derived molecules. Turmeric oil is also now used in aromatherapy and the perfume industry.

Taxonomy of the genus is quite confusing. A few studies on morphological and anatomical characterization of *Curcuma* species and turmeric varieties have been attempted, but not much has been done on molecular characterization except a few studies on isozyme polymorphism and identification of species based on 18S rRNA and trnK genes. Cytology of 12 species of *Curcuma* are reported. Taxonomic revision of the genus is now in progress in India and the number of Indian species may be narrowed down to 30 or so from the reported 40 species, as some of the species are now being treated as synonyms. Though *C. longa* syn. *Curcuma domestica* is the most commonly utilized species, other species such as *C. aromatica*, *C. amada*, *C. kwangsiensis*, *C. zedoaria*, *C. ceasia*, *C. malabarica*, *C. angustifolia*, *C. montana*, *C. decipiens*, *C. alismatifolia*, *C. thorelii*, *C. comosa* etc. are also economically important.

C. longa, cultivated turmeric, is now grown in countries like India, China, Pakistan, Bangladesh, Vietnam, Thailand, Philippines, Japan, Korea, Sri Lanka, Nepal, South Pacific Islands, East and West Africa, Malaysia, Caribbean Islands and Central America. India harbours rich diversity of *Curcuma*, especially species and cultivar diversity (Sasikumar *et al*., 1999). About 40 *Curcuma* species, ~50 cultivars and 20 improved varieties of *C. longa* and one improved variety of *C. amada* are available in India. India is the leading producer and exporter of turmeric in the world. Indian turmeric is exported to countries such as the UK, USA, Iran, Japan, United Arab Emirates, Saudi Arabia, the Netherlands, South Africa and Singapore in different forms such as whole dry rhizome, turmeric powder, turmeric oleoresin, curcumin, essential oil and curry powder.

Antiquity of turmeric

Turmeric with the sobriquet 'Indian Saffron' is one of the ancient medicinal, dye plants used by man. The antiquity of turmeric dates back to 'Atharva Veda' of 1000–1500 BC, a holy treatise of the Hindus, as 'Haldi' or 'Haridrar' (AV/1/22/4) (Shah, 1997). However, the ancient Indian system of medicine, Ayurveda (Science of Life), of approximately 5000 years of antiquity mentions the medicinal uses of turmeric. Interestingly, there is no mention of turmeric in the Bible or in the list of religious plants (Abbiw, 1993). Ethnobotanical evidence indicates that the use of turmeric has been in India since ancient days, connected with the 'Sakthi' worship or worship of Mother Goddess by the Pre-Aryan Indians.

Though it is widely acclaimed that the Indo-Malayan region is the centre of origin of *Curcuma*, the spread and acclimatization of turmeric in South and South-East Asia seem to have religious connections. It is assumed that the crop would have spread to different Asian countries under the influence of Hindu religion during the Post-Aryan period.

According to Marco Polo (1280), turmeric reached China in 700 AD (Ridley, 1912). Purseglove *et al.* (1981) stated that the people of Malagasy believed in a Malaya–Polynesian connection in the origin of turmeric in that country. Burkill (1966) believed that the crop spread to West Africa in the 13th and to East Africa in the 17th centuries. It was introduced to Jamaica in 1783. The introduction of turmeric to Central American countries is quite recent.

Species diversity

There are about 100 species in the genus *Curcuma*, 41 are known to occur in India (Table 1) of which at least 10 are endemic to the Indian subcontinent (M. Sabu, personal communication). The ecology of the species varies so much that their habitat ranges from sea level (sandy coastal habitat) to high altitude such as above 2000 m in the Western Ghats and Himalayas in India. While species such as *C. longa*, *C. zedoaria*, *C. amada* and *C. aromatica* are found predominantly in plains, *C. angustifolia*, *C. neilgherrensis*, *C. kudagensis*, *C. thalakaveriensis*, *C. pseudomontana* and *C. coriacea* etc. are confined to hills at 1000–2500 m altitude (Velayudhan *et al.*, 1999). Species diversity is at its maximum in south and north-east India and the Andaman and Nicobar Islands. The main discriminating features of the species are given in Table 2.

Taxonomic revision of the genus *Curcuma* is in progress. Since some of the existing species are now being recognized as synonyms such as *C. zedoaria* syn. *C. xanthorrihza* and *C. amada* closely resembles *C. mangga* for quality attributes it is likely that the number of species occurring in India may be reduced to just 30. Similarly, it has now been established that the Chinese species *C. albicoma* and *C. chuanyujin* are synonyms of *C. sichuanensis* and *C. kwangsiensis*, respectively. The Chinese species *C. wenyujin* is now recognized as a synonym of *C. aromatica*, *C. phaeocaulis* was misidentified in the past as *C. zedoaria*, *C. caesia* and *C. aeruginosa* in China (Liu and Wu, 1999). *C. kwangsiensis* var. *puberula* and var. *affinis* are not accepted and the identity of the Taiwan species *C. viridiflora* remains suspicious (Liu and Wu, 1999). However, new species, such as *C. rhabdota* are also reported from South-East Asia (Sirirugsa and Newman, 2000), *C. prakasha* sp. nov. from India (Tripathi, 2001), and *C. bicolor*, *C. glans* and *C. rhomba* from Thailand (Mood and Larsen, 2001). A list of economically more important species is given in Table 3.

Taxonomy

Curcuma belongs to the tribe Hedychieae. Though there are at present about 100 species in the genus, some of the species as discussed earlier are synonyms and it is believed that there may be only about 80 true species.

Table 1. *Curcuma* spp. reported from India

Sl. No.	Name of the species	Sl. No.	Name of the species
1	*C. aeruginosa* Roxb.	22	*C. mangga* Val. and Van Zijp.
2	*C. amada* Roxb.	23	*C. montana* Roxb.
3	*C. amarissima* Rosc.	24	*C. mutabilis* Skornickoa *et al.*
4	*C. angustifolia* Roxb.	25	*C. nilamburensis* Vel. *et al.*
5	*C. aromatica* Salisb.	26	*C. neilgherrensis*[a] Wight
6	*C. coriacea*[a] Sabu and Mangaly	27	*C. oligantha* Trim. var. *lutea*
7	*C. decipiens*[a] Dalz.	28	*C. petiolata* Roxb.
8	*C. ecalcarata*[a] Sivar and Indu.	29	*C. pseudomontana*[a] Grah.
9	*C. ferrugenia*[a] Roxb.	30	*C. purpurea* Blatt.
10	*C. caesia* Roxb.	31	*C. raktakanta*[a] Mangaly and Sabu
11	*C. caulina* Grah.	32	*C. rubrobracteata* Skornickoa *et al.*
12	*C. codonantha* Skornickoa *et al.*	33	*C. ranadei* Prain
13	*C. cordifolia* Roxb.	34	*C. reclinata* Roxb.
14	*C. haritha*[a] Mangaly and Sabu	35	*C. rubecens* Roxb.
15	*C. indora*[a] Blatter	36	*C. strobilifera* Wall.
16	*C. kudagensis*[a] Vel. *et al.*	37	*C. sulcata* Haines
17	*C. karnatakansis*[a] Vel. *et al.*	38	*C. thalakaveriensis* Vel. *et al.*
18	*C. latifolia* Rosc.	39	*C. vamana*[a] Mangaly and Sabu
19	*C. longa* L.	40	*C. xanthorrhiza* Roxb.
20	*C. longiflora* (Wall.) Rao and Verma	41	*C. zedoaria* Rosc.
21	*C. leucorrhiza*		

[a] Endemic species.

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Table 2. Important discriminating qualitative features of *Curcuma* spp.

	Variation
Character 1 (above-ground vegetative)	
Plant type	Erect, semi-erect
Leaf habit	Erect, semi-erect, prostrate
Sheath colour	Purple-green, light or dark purple, purple-brown, purple-green
Leaf margin	Highly wavy, medium wavy, low wavy
Leaf vein	Close, distant
Presence of hair on the dorsal side of the leaf	Hairy, glabrous
Presence of hair on the ventral side of the leaf	Hairy, glabrous
Leaf mid-rib colour	Green, light purple-green, light purple-brown
Leaf mid-rib fading	Absent, present
Inflorescence position	Central, lateral and both
Coma	Absent, present
Calyx colour	White, yellow, purple
Corolla colour	White, orange, red, purple, pale yellow, purple spot, blue
Staminode colour	White, red, pale yellow, orange, yellow
Anther spur	Absent, present
Nature of stigma	Exerted or appressed
Fertile bracts colour[a]	Red, purple, green, white
Fertile bract size and shape	Big, small, elongated conical, cupid, pad-like, spathe-like, oval, triangular, diamond
Character 2 (below-ground rhizome)	
Shape of root stock	Oblong, cylindrical
Colour of root stock	Reddish yellow, yellow, blue-black, blue-cream
Nature of rhizome	Sessile tubers present, no sessile tubers, stoloniferous (Fig. 3)
Presence of stipitate tubers	Absent, present
Presence of stolon	Absent, present
Shape of stipitate tubers	Fusiform, long fusiform
Aroma of rhizome	Mango aroma, camphoraceous aroma, turmeric aroma, no aroma
Taste	Bitter, sweet, inert, turmeric taste

[a] Fertile bract colour variation even within a species also exists. For example, *C. ecalcarata* has purple, deep purple and green bracts (Fig. 2a–c).

A comprehensive global taxonomic revision of the genus is yet to be attempted. The work of Valeton (1918) is considered to be a comparatively comprehensive attempt to study the taxonomy of the genus on a global level. Following Valeton's classification of the genus into two subgenera, namely *Paracurcuma* and *Ecurcuma*, Velayudhan *et al.* (1996) proposed a new conspectus of the genus in India. These authors found that the Indian species can be accommodated into the two subgenera of Valeton (1918) based on the presence or absence of anther spurs. *Eucurcuma* contains three main sections, namely *tuberosa*, *non tuberosa* and *stolonifera*, based on the presence or absence of tubers and stolons; each section again encompassing one or more subsections based on the aerial characters (floral and vegetative) and rhizome features. Under the subgenus *Paracurcuma*, only the anther spur lacking two species, namely *C. aurantiaca* and *C. ecalcarata*, are included. Prior to this, Mangaly and Sabu (1993) tried to revise the genus confined to south India representing a part of the diversity in the country. Clustering based on morphology, palynology and cytology of 14 Thai *Curcuma* species has also supported the Valeton's (1918) classification of the genus into two subgenera, namely *Eucurcuma* and *Paracurcuma* (Paisookasantivatana and Thepsen, 2001). Velayudhan *et al.* (1999) further grouped 568 *C. longa* collections into 21 distinct morphotypes based on vegetative, floral, rhizome and quality traits. These 21 morphotypes are divided into six taxonomic varieties, namely *C. longa* var. *typica*, *C. longa* var. *atypica*, *C. longa* var. *camphora*, *C. longa* var. *spiralifolia*, *C. longa* var. *musacifolia* and *C. longa* var. *platifolia*. Most of the morphotypes fall into *C. longa* var. *atypica* followed by *C. longa* var. *typica*.

Confusion, however, still persists on the taxonomy of the genus. The main problem in taxonomic studies of the genus are lack of type specimens and illustrations of old species, lack of paralogs and finer details in the earlier literature, absence of important floral parts in herbarium specimens, incomplete description of the rhizome feature in the herbarium sheets, fleshy and perishable aerial portions etc. Revision of Indian species is currently under way at the Department of Botany, University of Calicut, Kerala, India (Dr M. Sabu) and at the National Bureau of Plant Genetic Resources, Regional Station, Trissur, Kerala, India (Dr K. C. Velayudhan).

Table 3. Economically important species of *Curcuma*

Species	Use
C. longa L. syn *C. domestica* Val.	Spice, medicine, dye, religious local delicacies, insect repellent, aromatherapy and perfume
C. amada Roxb, *C. mangga* Val. and Zijp.	Spice, medicine, pickles and salads
C. zedoaria Roxb.	Folk medicine, arrowroot industry
C. ochrorhiza Val. and Van Zijp.	Malayan traditional medicine
C. pierreana Gagnep.	Vietnamese traditional medicine
C. aromatica Salisb.	Medicine, toiletry articles, insect repellent
C. kwangsiensis S. G. Lec and C. F. Liang syn *C. chuanyujin*, *C. phaeocaulis* Val.	Chinese traditional medicine
C. caesia Roxb.	Spice and medicine
C. comosa Roxb.	Traditional medicine of Thailand
C. angustifolia Roxb., *C. zedoaria* Roxb., *C. caulina* F. Grah, *C. pseudomontona* F. Grah, *C. montana* Roxb., *C. rubescens* Roxb. *C. leucorrhiza*, *C. xanthorrhiza* Roxb., *C. decipiens* Dalz., *C. malabarica* Vel. *et al.* *C. raktakanta* Mangaly and Sabu, *C. haritha* Mangaly and Sabu *C. aeruginosa* Roxb.	Arrowroot industry
C. alismatifolia Gagnep., *C. thorelii*, *C. roscoeana* Wall.	Ornamental (cut flower)

Characterization

Morphological characterization of Curcuma spp.

Velayudhan *et al.* (1999) studied 31 *Curcuma* spp. from India using numerical taxonomy tools. The 31 species could be clustered into nine groups in the dendrogram. By and large, the sessile tuberizing species were distinct from the species without sessile tubers. These authors also collected extensive data on distribution, habitat, flowering time, floral characters, quantitative characters of the floral parts, qualitative and quantitative features of above- and below-ground characters of the 31 *Curcuma* spp. Most of the species exhibited distinguishable morphological features.

Curcuma species database

Remya *et al.* (2003) developed a database in Visual Basic for *Curcuma* species of India using some of the discriminative traits listed in Table 2, in MS Access, which is retrievable by serial number or species name.

Cytology of Curcuma spp.

Saigura (1936) was the first to report the somatic chromosome number of *C. longa*. Later several authors have reported the chromosome number of some of the economically important *Curcuma* spp. (Table 4). Different somatic chromosome numbers are reported in some of the species.

Anatomy

Sherlija *et al.* (1998) studied the rhizome anatomical characters of four *Curcuma* spp., namely *C. longa*, *C. aromatica*, *C. amada* and *C. zedoaria*. Though all four species had similar basic anatomical traits, variation was noted with respect to the arrangement of primary and secondary vascular bundles, orientation of endodermoid layer, number and shape of starch grains and curcumin cells among the species. *C. longa* had the maximum number and size of curcumin cells. The endodermoid layer formed a continuous ring along with the pericycle in *C. longa* whereas it was more or less circular in *C. amada*. In *C. aromatica* and *C. zedoaria* the endodermoid layer was discontinuous and wavy in nature. Gogoi *et al.* (2002) reported variation in the morphology of epidermal cell walls, nature and number of epidermal cells per unit area, stomatal frequency and index besides trichome length in three *Curcuma* spp., namely *C. longa*, *C. caesia* and *C. zedoaria*. Variations in the stereoscopic features of leaf epidemis (density, size and shape of epidermal cells, average perimeter of epidermal cells, average sectional area of the lower epidermis, stomatal density and trichome distribution of upper and lower epidermis) of some *Curcuma* spp. are reported from China (Xiao *et al.*, 2001).

Chemical profiling of Curcuma spp.

Curcumin, essential oil and oleoresin are the three most important biochemical components found in *Curcuma*

Table 4. Chromosome number of some economically important species of *Curcuma*

Species	Chromosome number	Reference
C. amada	$2n = 42$	Raghavan and Venkatasubban (1943), Chakravorti (1948), Raghavan and Arora (1958), Sharma and Bhattacharyya (1959), Ramachandran (1961)
C. angustifolia	$2n = 42$, $2n = 64$	Chakravorti (1948), Sharma and Bhattacharyya (1959)
C. aromatica	$2n = 42$, $2n = 63$, $2n = 86$	Raghavan and Venkatasubban (1943), Chakravorti (1948), Ramachandran (1961)
C. decipiens	$2n = 42$	Raghavan and Venkatasubban (1943)
	$2n = 32$	
C. longa	$2n = 62$	Raghavan and Venkatasubban (1943), Sharma and Bhattacharyya (1959)
	$2n = 62, 63, 64$	Chakravorti (1948)
	$2n = 63$	Ramachandran (1961)
	$2n = 64$	Saigura (1936)
C. neilgherrensis	$2n = 42$	Ramachandran (1961)
C. petiolata	$2n = 64$	Raghavan and Venkatasubban (1943)
C. zedoaria	$2n = 63$	Ramachandran (1961)
	$2n = 63, 64$	Chakravorti (1948)
C. caesia, *C. haritha*	$2n = 42$	
C. malabarica	$2n = 63$	
C. raktakanta	$2n = 63$	
C. aeruginosa	$2n = 63$	Joseph *et al.* (1999)

spp. While *Curcuma longa* is rich in total curcumin (2–7%), oleoresin (7–15%) and essential oil (2–5%), other *Curcuma* spp. are low in these components. Though not much literature on the proportion of the curcuminoids in various *Curcuma* spp. are available, many gas chromatography or gas chromatography–mass spectrometry studies are there on the volatile aroma profile variation in essential oil of some of the *Curcuma* spp. (Table 5).

Different authors have reported different profiles of essential oil for the same species or for same plant parts. Even the same authors have also reported different values for essential oil profile in a single species or same plant parts in different papers. This anomaly may be due to the effect of environments, varieties, maturity variations, analytical techniques or even incorrect taxonomic identification of the specimens. Nevertheless, *Curcuma* species vary widely in their essential oil profile.

Molecular characterization

Interspecific molecular characterization of the genus is in a nascent stage. Sreeja (2002) characterized five *Curcuma* spp., namely *C. longa*, *C. zedoaria*, *C. caesia*, *C. amada* and *C. aromatica*, based on randomly amplified polymorphic DNA (RAPD) profiling of rhizome DNA. Three random decamer primers generated 11 polymorphic bands among the species studied. A novel attempt to identify the genuine *Curcuma* species traded as drugs in China and Japan based on sequence analysis of the 18S rRNA and trnK genes coupled with amplification refractory mutation system (ARMS) analysis was done by Sasaki *et al.* (2002). Though designed to identify the spurious *Curcuma* spp. in the marketed drugs, this method is also helpful in the molecular taxonomy of *Curcuma*. The authors could trace the botanical origin of Chinese and Japanese *Curcuma* drugs to *C. longa*, *C. phaeocaulis* and *C. zedoaria* (Japan) and *C. kwangsiensis*, *C. wenyujin* and *C. aromatica* (China) based on the comparison of 18S rRNA and trnK gene sequences with those of six *Curcuma* species reported earlier. Further, to develop a more convenient identification method, ARMS analysis of both gene regions was also performed on live plants, using specially designed forward primers for 18S rRNA and four types of specific reverse primers for the trnK gene. DNA fragment specific to each species could be identified. Sasikumar *et al.* (2004) have developed a PCR technique to identify the genuine botanical *Curcuma* species in the marketed turmeric powder. RAPD markers for identifying *C. longa* and *C. zedoaria* in the marketed turmeric powder are reported.

Apavatjrut *et al.* (1999) studied isozyme polymorphism in seven early flowering and two unidentified *Curcuma* species of Thailand. Out of the 21 isozymes studied, eight isozymes were found to be polymorphic and the species were grouped into distinct clusters depicting their phylogenetic relationships. Comparative isozyme polymorphism of the cultivated and natural populations of *C. alismatifolia* from Thailand and Japan revealed that the cultivated population is more uniform genetically (Paisookasantivatana *et al.*, 2001).

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Table 5. Composition of essential oil of different species of *Curcuma*

Species	Compound	Reference
C. longa (leaves)	α-Pinene (1.45), β-pinene (2.29), 1,8-cineole (10.74), camphor (1.4), linalool (11.95), β-phellandrene (12.61), geraniol (6.72) and *cis*-β-ocimene (13.76)	Behura (2000)
C. longa (leaves)	α-Pinene (2.8), β-pinene (4.0), myrcene (48.8), β-ocimene (*E* and *Z*) (2.0), limonene (2.5), 1,8-cineole (6.4), *p*-cymene (4.3), terpinolene (10.1), methyl eugenol (1.3), eugenol (1.8) and tamesol (1.8)	Behura and Srivastava (2004)
C. longa (leaves)	Myrcene (5.3), limonene (3.6), 1,8-cineole (3.4) and terpinolene (87.8)	Behura and Srivastava (2004)
C. longa (leaves)	α-Pinene (2.88), β-pinene (2.36), sabinene (0.4), myrcene (1.17), α-phellandrene (38.24), 1,8-cineole (8.64), *p*-cymene (6.05), C_8-aldehyde (20.58), linalool (0.58), caryophyllene (0.70), geraniol (1.77) and methyl heptanone (0.05)	Behura *et al.* (2002)
C. longa (leaves)	Tricyclene (0.1), α-pinene (0.7), α-fenchene (0.1), sabinene (0.1), β-pinene (0.7), myrcene (1.4), δ-2-carene (0.1), α-phellandrene (2.8), δ-3-carene (1.2), α-terpinene (3.7), *p*-cymene (0.3), 1,8-cineole (4.6), (*Z*)-β-cineole (0.4), (*E*)-β-cineloe (0.7), γ-terpinene (0.4), terpinolene (76.8), linalool (0.7), *p*-mentha-1,3,8-triene (0.2), *p*-cymene-8-ol (0.2), α-terpineol (0.3), β-caryophyllene (0.1), (*E*)-β-farnesene (0.1), ar-curcumene (0.1), zingiberene (1.0), β-bisabolene (0.1), β-sesquiphellandrene (0.4), (*E*)-nerolidol (0.1), (*Z*)-γ-atlantone (0.1) and germacrone (0.1)	Chane-Ming *et al.* (2002)
C. longa (leaves)	α-Phellandrene (18.28), α-pinene (14.65), *p*-cymene (13.35) are identified as the major constituents	Sharma *et al.* (1997)
C. longa (rhizome)	α-Pinene (0.512), β-pinene (0.77), linalool (1.35), caryophyllene (1.02), borneol (1.48), turmerone (11.33), ar-turmerone (30.54) and *cis*-β-ocimene (9.76)	Behura (2000)
C. longa (rhizome)	α-Pinene (0.2), myrcene (0.3), α-phellandrene (1.0), δ-3-carene (0.3), α-terpinene (1.4), *p*-cymene (0.6), 1,8-cineole (2.0), *p*-cymenene (0.4), terpineolene (15.8), terpinen-4-ol (0.2), *cis*-α-bergamotene (0.3), β-caryophyllene (5.7), α-humulene (1.4), (*E*)-β-farnesene (0.6), ar-curcumene (4.5), zingiberene (11.8), β-bisabolene (1.9), β-sesquiphellandrene (8.8), (*E*)-γ-bisabolene (0.7), (*E*)-nerolidol (0.2), ar-turmerol (0.3), ar-dihydro turmerone (0.6), ar-turmerone (7.7), α-turmerone (21.4), β-turmerone (7.1) and curcuphenol (0.2)	Chane-Ming *et al.* (2002)
C. longa (rhizome)	β-Turmerone (30–32), ar-turmerone (17–26) and β-turmerone (15–18)—major compounds	Sharma *et al.* (1997)
C. longa (rhizome)	ar-Turmerone (24.78), turmerone (29.58), turmerol (20.0) and α-atlantone (2.4)	Zwaving and Bos (1992)
C. aromatica (leaves)	α-Pinene (4.77), β-pinene (3.7), myrcene (0.39), 1,8-cineole (28.01), *p*-cymene (1.45), caryophyllene (2.01), α-phellandrene (1.40), C_8-aldehyde (2.62) and geraniol (1.28)	Singh *et al.* (2003)
C. aromatica (leaves)	α-Pinene (4.77), β-pinene (3.7), sabinene (0.68) myrcene (0.39), α-phellandrene (1.4), 1,8-cineole (28.01), *p*-cymene (1.45), C_8-aldehyde (2.62), linalool (7.67), caryophyllene (2.01) and geraniol (1.28)	Behura *et al.* (2002)
C. aromatica (leaves)	1,8-Cineole (20), camphor (18), germacrone (11.8), isoborneol (6.4), camphene (9.4) and limonene (8.6)	Choudhury *et al.* (1996)
C. aromatica (leaves)	Camphor (25.58), ar-turmenene (13.2), curzerenone (6.2), 1,8-cineole (6.0) and α-turmerone (2.5)	Bordoloi *et al.* (1999)
C. aromatica (rhizome)	1,8-Cineole (9.3), camphor (25.6), germacrone (10.6), isoborneol (8.2), camphene (7.4) and curzerenone (10.9)	Choudhury *et al.* (1996)
C. aromatica (rhizome)	ar-Curcumene (18.6), β-curcumene (25.5) and xanthorrhizol (25.7)	Zwaving and Bos (1992)
C. aromatica (rhizome)	Curdione, germacrone, 1,8-cineole, germacrone-4,5-epoxide, β-elemene and linool	Kojima *et al.* (1998)
C. aromatica (rhizome)	α-Pinene (4.8), α-camphene (2.7), β-pinene (5.8), azulene (0.5), l-zingiberene (10.7), 1-ar-curcumene (14.6), 1-β-curcumene (33.8), camphor (3.2), α-terpineol (7.8), cuminyl alcohol (5.5), de-borneol (5.3) and zingiberol (3.5)	Rao and Nigam (1974)
C. aromatica (rhizome)	Camphor (32.3), curzerenone (11.0), α-turmerone (6.7), ar-turmerone (6.3) and 1,8-cineole (5.5)	Bordoloi *et al.* (1999)

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Table 5. *Continued*

Species	Compound	Reference
C. amada (rhizome)	α-Pinene (0.7), β-pinene (4.64), myrcene (80.54), β-ocimene (*E* and *Z*) (2.1), perillene (1.47), limone (0.13), camphor (trace), curzerenone (0.14), 1,8-cineole (0.06) and camphene (0.18)	Singh *et al.* (2003)
C. amada (rhizome)	α-Pinene (0.9), β-pinene (4.9), myrcene (0.2), β-ocimene (*E* and *Z*) (0.4), perillene (0.4), limonene (0.1) and α-pinene (0.1)	Choudhury *et al.* (1996)
C. amada (rhizome)	α-Pinene (0.4), β-pinene (0.6), myrcene (0.2), limonene (0.4), camphor (11.2), β-elemene (2.8), isoborneol (4.5), β-curcumene (11.2), curzerenone (7.1), ar-curcumene (28.1), α-pinene (6.0), linalool (0.4), zingiberene (1.4) and camphene (0.18)	Srivastava *et al.* (2001)
C. amada (rhizome)	α-Pinene (18.0), β-ocimene (*E* and *Z*) (47.2), linalool (11.2), linyl acetate (9.1) and safrole (9.3)	Dutt and Tayal (1941)
C. amada (rhizome)	α-Pinene (0.49), β-pinene (0.72), camphor (0.33), linalool (1.3), β-phellandrene (6.85), turmerone (10.8), ar-turmerone (29.12) and *cis*-β-ocimene (18.79)	Behura (2000)
C. caesia (leaves)	α-Pinene (1.5), β-pinene (6.3), myrcene (0.5), limonene (2.1), 1,8-cineole (27.0), camphor (1.68), linalool (2.8), β-elemene (2.4), borneol (8.7), α-terpenol (5.2) and eugenol (2.0)	Behura and Srivastava (2004)
C. caesia (rhizome)	α-Pinene (0.40), β-pinene (0.60), β-ocimene (*E* and *Z*) (2.1), camphor (7.73), linalool (0.99), caryophyllene (3.15), borneol (4.3), camphene (1.67), anethole (1.79) and *cis*-β-ocimene (14.54)	Behura (2000)
C. aeruginosa (leaves)	Curzerenone (16.2), germacrone (3.6), 1,8-cineole (13.5) and camphor (5.7) (total 25 compounds)	Nguyen *et al.* (1995a)
C. aeruginosa (leaves)	1,8-Cineole (17.7), curzerenone (10.5), furanogermenone (7.0), camphor (7.5), (2)-3-hexanol (5.08), furanodienone (5.1), curcumenol (4.5), isocurcumenol (3.7) and β-elemene (3.3)	Jirovetz *et al.* (2000)
C. aeruginosa (rhizome)	Curzerenone (24.68), 1,8-cineole (11.6), camphor (16.6), zedoarol (6.3), isocurcumenol (5.8), curcumenol (5.6) and furanogermanone (5.5) (total 26 compounds)	Sirat *et al.* (1998)
C. aeruginosa (rhizome)	Isocurcumenol (8.5), β-eudesmol (6.5), curdione (3.6), curcumenol (9.9), curcumenolides A, B (11.4), dehydrocurdione (9.4) and curcumenone (1.9)	Zwaving and Bos (1992)
C. xanthorrhiza (rhizome)	ar-Curcumene (41.4) and xanthorrhizol (21.5)	Zwaving and Bos (1992)
C. heyneana (rhizome)	1,8-Cineole/limonene (14.2), isocurcumenol (7.4), β-eudesmol (4.78), curcumanolides A, B (13.18), dehydrocurdione (10.2) and curcumenone (2.3)	Zwaving and Bos (1992)
C. harintha (rhizome)	α-Pinene (1.75), β-pinene (6.67), *p*-cymol (2.89), camphor (21.24), camphene (14.59), borneol (1.37), terpinyl acetate (2.43), pentadecane (1.84), turmerone (5.39), ar-turmerone (9.63) and ethyl *p*-methoxycinnamate (3.53)	Dan *et al.* (2002)
C. raktakanta (rhizome)	α-Pinene (5.25), β-pinene (13.42), camphor (12.78), terpinyl acetate (3.43), bornyl acetate (2.82), ethyl cinnamate (4.23), caryophellene (11.25), tridecane (3.87), turmerone (5.31) and ethyl *p*-methoxycinnamate (16.57)	Dan *et al.* (2002)
C. pierreana (leaves)	Camphor (13.0) and isoborneol (12.8) (more than 35 compounds are identified)	Nguyen *et al.* (1995b)
C. pierreana (stem)	Isoborneol (12.4), isobronyl acetate (14.4), β-caryophellene (10.4) and *Z*-β-farnesene (10.8) (more than 35 compounds are identified)	Nguyen *et al.* (1995b)
C. pierreana (rhizome)	Isoborneol (22.9) and isobornyl acetate (18.8) (more than 30 compounds are identified)	Nguyen *et al.* (1995b)
C. trichosantha (rhizome)	Curdione (47.48), curcumol (7.0) and germacrone (6.1)	Pham *et al.* (1994)
C. mangga (rhizome)	Myrcene (78.68), (*E*)-β-ocimene (5.1), β-pinene (3.7) and pinene (2.9)	Wong *et al.* (1999)
C. ochrorhiza (rhizome)	Furanogermenone (53.24), germacrone (9.62), β-elemene (8.84), camhor (6.31) and α-isofuranodiene (5.6)	Sirat *et al.* (1997)
C. harmandii (leaves)	1,8-Cineole (13.5), germacrone (11.5) and curdione (36.8)	Nguyen *et al.* (1997)
C. harmandii (stem)	1,8-Cineole (21.8), germacrone (15.5) and curdione (25.3)	Nguyen *et al.* (1997)

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Table 5. *Continued*

Species	Compound	Reference
C. harmandii (small rhizome—finger)	1,8-Cineole (12.5), germacrone (9.0) and curdione (22.6), β-elemene (11.3) and α-isocurcumenol (3.7)	Nguyen *et al.* (1997)
C. harmandii (big rhizome—mother)	1,8-Cineole, (4.5), germacrone (20.5), β-pinene (1.2), β-elemene (6.5) and isocurcumenol (13.4)	Nguyen *et al.* (1997)

Figures in parentheses are percentage values.

Characterization of C. longa varieties

Genetic variability for yield, yield attributes and curcumin content in turmeric have been reported by many workers (Mathai, 1976; Ratnambal, 1986; Geetha and Prabhakaran, 1987; Sasikumar and Sardana, 1989; Nirmal Babu *et al.*, 1993; Chandra *et al.*, 1997, 1999; Lynrah *et al.*, 1998; Hazra *et al.*, 2000). Environmental effects on curcumin content of turmeric varieties is also reported (Zachariah *et al.*, 1998) and curcumin content of the turmeric varieties generally show high location × genotype effect. Turmeric cultivars are classified either as short, medium or long duration as well as high or low curcumin varieties (Sasikumar *et al.*, 1994).

Shamina *et al.* (1998) studied isozyme polymorphism in a germplasm collection of *C. longa*. Acid phosphatase, superoxide dismutase, esterase, polyphenol oxidase, peroxidase and catalase showed good polymorphism in the 15 accessions studied. Though turmeric (*C. longa* L.) is predominantly vegetatively propagated, the variability observed for the isozymes indicate the role of natural selection and conscious selection by man over the years in evolving locally adapted cultivars.

Uses

Religious

Ethnobotanical evidence indicates that the use of turmeric has been there in India since ancient days connected with the religious worship and tantric or magic rites of Pre-Aryan Indians. Hence Sopher's (1964) remark that turmeric was rather a material of magic property and colouring source in the beginning and later on became a medicine and spice. Even today in India and some far-eastern Asian nations, turmeric forms a part of Hindu religious customs and practices. Turmeric assumes ambrosias in India because of its association with worship of Hindu deities such as 'Kali' (Mother Goddess) and 'Naga' (Serpent deity). In Kerala, India dried turmeric powder, rice powder and a few other plant-derived powders are used as colouring materials in making and decorating the huge 'Kalams' of various deities connected with 'Sakthi' worship (Mother Goddess) or worship of certain other gods of the Hindus which is locally known as 'Kalamezhuthupattu', a folklore tradition even today. Turmeric plus lime known as 'Kumkum' (a sort of natural vermilion), distributed to the devotees in the temples, is applied on the forehead, and is believed auspicious by the Hindus. Turmeric powder along with sandal powder are used in preparing 'Kalabha' to be poured on the presiding deities in temples. Married Hindu women apply 'Kumkum' on their forehead longitudinally along the hair partition path to indicate the marital status or smear turmeric paste on either side of the cheek. Turmeric powder when mixed with lime produces a red coloured material due to formation of metallic compounds of curcumin.

In North India, a red dye locally known as 'pithyan' or 'roli' prepared from turmeric is smeared on the forehead with thumb or middle finger on religious occasions or ceremonies. The red colour of 'pithyan' is due to the formation of rosocyanin and rubrocurcumin (Tonnesen, 1986). The folk chemistry of 'pithyan' is as below:

Turmeric rhizome + lime juice

+ 'Suhaga' (borax) [keep in copper bowl for 5–6 days]

→ rhizome (red) [ground] → 'pithyan' or 'roli'.

The curcumin in turmeric when it comes in contact with boric acid in the presence of mineral acid yields rosocyanin and rubrocurcumin resulting in the red-coloured powder (Shah, 1997).

In India, turmeric is used as invitational material during wedding or other auspicious ceremonies of Hindus. Invitation cards (on the four corners) are stained with turmeric solution to make them auspicious. Turmeric powder mixed with mustard oil is smeared on the body of the bride and bridegroom in some parts of India. In southern India 'Mangalyasutra' (cotton thread carrying the 'thali'—a heart-shaped golden locket—worn around the neck at the time of marriage by Hindu women) is coloured with turmeric. Indonesian women decorate their palms with turmeric. Turmeric is also used in

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sorcery. It is believed that keeping a piece of turmeric saves a person from evil eyes.

Traditional foods

A traditional delicacy 'Kadbu' (a sweet made from steaming rice paste wrapped in fresh turmeric leaves) is prepared during the Hindu festival of 'Ganesha Chaturthi' in Karnataka, India. Turmeric chutney, turmeric pickle, salad from immature turmeric rhizome, 'tumbli' (coconut curd-based appetiser made with turmeric rhizome) are some other turmeric-based delicacies in rural India.

Folk medicine

Curcuma species such as *C. longa*, *C. aromatica*, *C. caesia*, *C. zedoaria* (India, China, Thailand, Vietnam, etc.), *C. kwangsiensis*, *C. wenyujin* (=*C. aromatica*), *C. phaeocaulis* (China) and *C. comosa* (Thailand) have been used in a variety of folk human and veterinary medicines. A paste of turmeric is smeared topically on the head in vertigo, on body sprains, swellings, cuts, wounds, injuries, skin infection, poisonous insect/snake/scorpion bites, pimples and foul ulcers; common cold, bronchitis and internal fevers (oral); flatulence, indigestion and diarrhoea (oral); bilary and hepatic disorders, anorexia, diabetic wounds (external or internal) in the Indian countryside. Inhaling fumes of dried turmeric rhizome is also a common practice in India for sinusitis, catarrh, coryza, fits etc. After delivery women are given a body massage with turmeric powder mixed with mustard oil to relieve inflammatory affections of joints (topical) besides administering orally a mixture of turmeric, dried ginger, *Acacia nilotica*, *Trachyspermum ammi* plus sugar (Shah, 1997). Turmeric powder or paste is smeared on the severed umbilical chord of the newborn babies by the Indian rural folk, as an antiseptic practice. Poultice of turmeric, wheat flour, castor oil and salt is an effective remedy for easing out plant thorns stuck on a toe.

C. aromatica (=*C. wenyujin*) is used in Chinese medicine as the main source of 'yujin', an alternative source of 'ezhu' and rarely a source of 'jianghuang'. *C. kwangsiensis* is used as an alternative source for 'ezhu' and sometimes for 'yujin'. *C. longa* is the main source of 'jianghuang' and sometimes a source for 'yujin' too. *C. zedoaria* is the main source of 'ezhu' in Chinese medicine as well as an alternative source of 'yujin' (http://www.itmonline.org/arts/turmeri3.htm). Turmeric (*Curcuma* spp.) is generally used as a stimulant, aspirant, carminative, cordeal, emenagogue, astringent, detergent, diuretic and martirnet in Chinese medicine.

In traditional veterinary medicine turmeric or *Curcuma* also plays an important role. Fresh turmeric and garlic ground together and mixed in water is given to newly hatched chickens by the rural poultry farmers in India. Turmeric poultice is also applied to broken legs of chickens, ducks and other domestic birds. Turmeric is also administered internally against Raniket disease of birds. Young puppies are given a massage with coconut oil impregnated with turmeric powder and sulphur to prevent hair fall. Turmeric ground with neem leaf is applied in case of scabies in cattle and to heal cuts and wounds in cattle, dogs and other animals. Turmeric ointment prepared in ghee and white petroleum jelly is used in the treatment of abscesses and wounds of cattle (Mandal and Chauhan, 2000). Juice of fresh rhizome of turmeric is applied to recent wounds, bruises and leech bites in domestic animals. A paste of turmeric and neem leaf is used in ringworm infection, itching, eczema and other parasitic diseases of cattle. A boiled mixture of turmeric (640 g), clarified butter (500 g), milk (1.5 litres) and sugar (120 g) mixed with black pepper, ginger and cinnamon is administered at a dose of 10 ml in the morning in the case of prurigo, boils, urticaria and chronic skin eruptions of domestic animals (Sharma and Joshi, 2004).

Validation of the folk medicinal value of turmeric in treating skin diseases of camel and buffalo (Chhabra *et al.*, 1994) and sub-clinical mastitis in cattle (Joshi *et al.*, 1996) are reported. Use of common turmeric (*Curcuma longa*) in controlling endoparasites, external and internal injuries, and pregnancy-related problems of ruminants are documented in Trinidad and Tobago (Lans and Brown, 1998). Effective mastitis treatment in cows using gel (Mastelep AV/AMP/4) containing turmeric is reported from India by Buragohain and Dutta (1998). Anti-inflammatory activity of the extracts of *C. aromatica* in cattle is also reported (Jangde *et al.*, 1998).

Biological activity of turmeric and its components

Curcuminoids (curcumin, demethoxy curcumin, bisdemethoxy curcumin, methyl curcumin and acetyl curcumin), volatile oil components from rhizomes and leaves of *Curcuma* species besides ethanol, crude ether, chloroform and water extracts of turmeric powder as well as powdered or ground turmeric are very important biologically (Fig. 1a–i). In fact, the relative proportion of the different curcuminoids plays a considerable role in optimum bioprotective activity of turmeric. The concept of a curcumin C_3 complex stamped with a specific concentration limit of the individual curcuminoid is an offshoot of this finding (Varghese, 1999). As in case of the essential oil (Table 5), the curcuminoids in different *Curcuma* species are bound to vary, though reports are not available except in case of *C. longa* and *C. xanthorrhiza* (Lechtenberg *et al.*,

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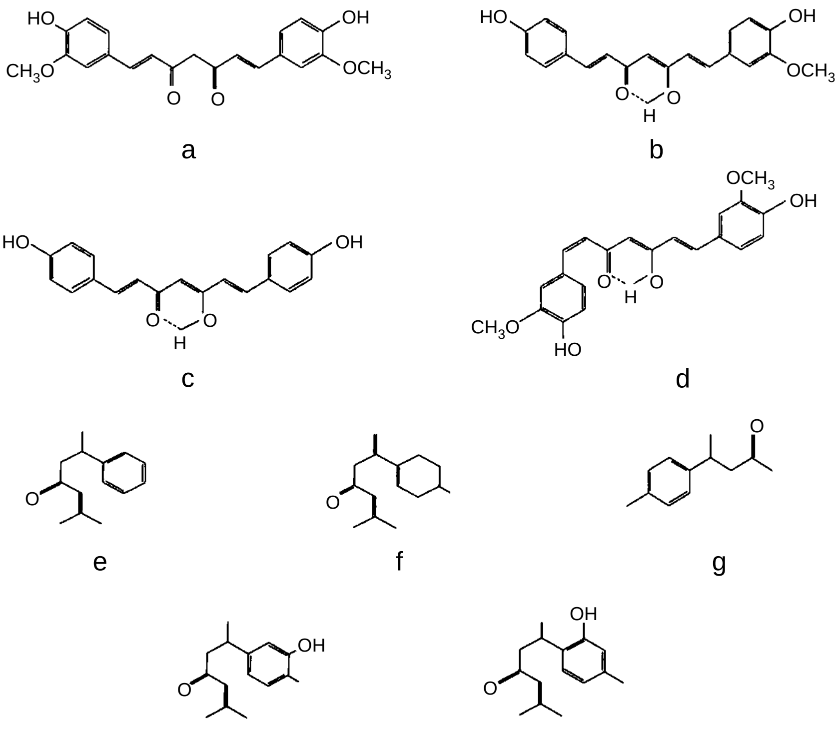

Fig. 1. Chemical structure of biologically active compounds from turmeric: (a) curcumin; (b) demethoxy curcumin; (c) bis-demethoxy curcumin; (d) *cis–trans* geometrical isomer of curcumin; (e) ar-turmerone; (f) turmerone; (g) curcumone; (h) turmeronol A; (i) turmeronol B.

2004). However, *C. longa* is the major source of curcuminoids and volatile oil. Even within *C. longa*, variation in curcuminoid concentration is known to occur from variety to variety (Wang *et al.*, 1999). Jayaprakasha *et al.* (2002) studied the variation of three curcuminoids in four different commercial varieties of turmeric, namely 'Salem', 'Erode', 'Balasore' and 'Mysore'. The percentage of curcumin, demethoxy curcumin and bis-demethoxy curcumin were found to be 1.06 ± 0.061 to 5.65 ± 0.040, 0.83 ± 0.047 to 3.36 ± 0.040 and 0.42 ± 0.036 to 2.16 ± 0.06, respectively in the four samples. The total percentages of curcuminoids are 2.34 ± 0.171 to 9.18 ± 0.232. Table 6 (revised and updated from Chattopadhyay *et al.*, 2004) gives the biological activity of the different compounds of *Curcuma*. The pharmacological action of curcumin as well as clinical studies and medicinal application of turmeric and its compounds are reviewed in Chattopadhyay *et al.* (2004).

Turmeric powder has a beneficial effect on the stomach as a gastro protectant (Lee *et al.*, 2003). However, there exists some controversy regarding antiulcer activity of curcumin as both antiulcer and ulcerogenic findings are reported (Sinha *et al.*, 1974; Kato *et al.*, 1998). Curcumin is shown to protect the stomach from the ulcerogenic effect of phenyl butazone in guinea pigs and other animals (Sinha *et al.*, 1974). Van Dau *et al.* (1998) has reported a healing effect of turmeric on duodenal ulcers. Recent studies in rats have shown that curcumin can block indomethacin, ethanol and stress-induced gastric ulcer and can also prevent pylorus-legation-induced acid secretion (Chattopadhyay *et al.*, 2004).

Curcumin can also have a protective effect on intestines and liver. Antispasmodic activity of sodium curcuminate was observed in isolated guinea pig ileum (Srihari Rao *et al.*, 1982) as well as antiflatulent activity in rat intestine (Bhavani-Shankar and Sreenivasa-Murthy, 1979). A protective role of curcumin and its analogues in cultured rat hepatocytes against carbon tetrachloride, D-galactosamine, peroxide and ionophore-induced toxicity have been reported (Hikino, 1985; Park *et al.*, 2000). Lalitha *et al.* (1999) also recorded the beneficial effect of aqueous extract of turmeric in CC 14-induced hepatotoxicity. Administration of curcumin to rats fed alcohol (25% content) decreased the activities of alkaline phosphates, aspartate transaminase and levels of fucose and sailic acid (Rajakrishnan and Menon, 2002).

Latest studies revealed that *C. longa* could be a source of a new drug molecule to combat Alzheimer's disease by protecting the brain cells from β-amyloid insult (Park and Kim, 2002). The neuroprotective role of curcumin in ethanol-induced brain damage is also reported (Rajakrishnan *et al.*, 1999). Curcumin and manganese

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Table 6. Biological activities of turmeric and its components (revised and updated from Chattopadhyay *et al.*, 2004)

Compounds/extract	Biological activity	Reference
Turmeric powder	Wound healing	Gujral *et al.* (1983)
	Anti-inflammatory	Yegnanarayan *et al.* (1976)
	Hypolipidaemic	Dixit *et al.* (1988)
	Antitumour	Kuttan *et al.* (1985)
	Antiprotozoan	Dhar *et al.* (1968), Rasmussen *et al.* (2000)
Petroleum extract	Anti-inflammatory	Yegnanarayan *et al.* (1976)
	Antifertility	Garg (1974)
Alcohol extract	Antibacterial	Bhavani-Shankar and Sreenivasa-Murthy (1979)
Crude ether extract	Antifungal	Misra and Sahu (1977)
Chloroform extract	Antifungal	Misra and Sahu (1977)
Aqueous extract	Antifertility	Garg (1974)
	Antifungal	Kapoor (1998)
Volatile oil	Insect repellency	Tripathi *et al.* (2001), Pitasawat *et al.* (2003), Leun Mau *et al.* (2003)
	Anti-inflammatory	Chandra and Gupta (1972)
	Antibacterial	Bhavani-Shankar and Sreenivasa-Murthy (1979)
	Aphid vector control	Khanna (1999)
	Antifungal	Banerjee and Nigam (1978), Kapoor (1998)
Curcumin	Antibacterial	Lutomski *et al.* (1974)
	Antiprotozoan	Bhavani-Shankar and Sreenivasa-Murthy (1979)
	Antitoxicity	Rajakrishnan and Menon (2002)
	Antiviral	Mazumdar *et al.* (1995)
	Pollution control	Varma *et al.* (1998)
	Anti-inflammatory	Rao *et al.* (1970), Ramsewak *et al.* (2000)
	Antiarthritic	Chandra and Gupta (1972)
	Antithrombotic	Srivastava *et al.* (1985)
	Antimutagenic	Nagabhushan and Bhide (1987), Polasa *et al.* (1990)
	Hypolipidaemic	Rao *et al.* (1970)
	Hypoglycaemic	Blasiak *et al.* (1999)
	Anticoagulant	Srivastava *et al.* (1985)
	Antioxidant	Sharma (1976), Srinivas *et al.* (1992), Ramsewak *et al.* (2000)
	Estimation of boron in solutions and biological sample	Winner and Goldbatch (1999)
	Antilipid peroxidase	Sharma *et al.* (1972)
	Antitumorous	Deeb *et al.* (2003)
	Anticarcinogenic	Chen *et al.* (1996)
Turmerin	Antioxidant	Srinivas *et al.* (1992)
Ar-turmerone	Antivenomous	Ferreira *et al.* (1992)
Methyl curcumin	Antiprotozoan	Gomes *et al.* (2002)
Demethoxy curcumin	Antioxidant	Unnikrishnan and Rao (1995)
Bis-demethoxy curcumin	Antioxidant	Unnikrishnan and Rao (1995)
Sodium curcuminate	Anti-inflammatory and antibacterial	Ramprasad and Sirsi (1956)

complex of curcumin offer protection against vascular dementia due to antioxidant activity (Vajragupta *et al.*, 2003; Thiyagarajan and Sharma, 2004). Curcumin reduces low and very low density lipoproteins in plasma and total cholesterol levels in liver (Kamal Eldin *et al.*, 2000).

Curcumin is effective against carrageenin-induced oedema in rats and mice (Srivastava and Srimal, 1985; Bronet and Ohshima, 1995). Though whole turmeric powder and curcumin have antidiabetic properties, rat studies have shown that curcumin is more effective than turmeric as such in attenuating diabetes mellitus (Narayanasamy *et al.*, 2002). The antirheumatic effect of curcumin has also been established in patients by administering turmeric (Srimal and Dhawan, 1985). Singh and Aggarwal (1995) and Surh *et al.* (2001) have reported the mechanism of action of the anti-inflammatory effect of curcumin.

The antioxidant activity of curcumin and turmeric is important directly as a biomedical compound and also as a food additive to prevent the oxidation and resultant rancidity of oils and fats during storage (Sharma, 1976;

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Khanna, 1999). Anti-oxidant activity of the curcumin is either due to the suppression of reactive oxygen species (ROS) or scavenging the free radicals (Joe and Lokesh, 1994; Unnikrishnan and Rao, 1995; Chattopadhyay *et al*., 2004). However, pro-oxidant activity of curcumin is also reported in biological systems (Kelly *et al*., 2001; Galati *et al*., 2002). Positive effects of curcumin in myocardial infarction and thrombosis are known (Nirmala and Puvanakrishnan, 1996; Olajide, 1999).

The anticancerous effect of curcumin is mainly due to induction of apoptosis and inhibition of cell cycle progression (Chen and Huang, 1998) besides inhibiting iNOS and COX-2 production (Bronet and Ohshima, 1995).

A chemoprotective role of curcumin in human colon cancer (Kawamori *et al*., 1999), human leukaemia HL-60 cells (Kuo *et al*., 1996) and human breast carcinoma (Shao *et al*., 2002) is also reported.

Petroleum ether extract and aqueous extract of turmeric rhizome show 100% antifertility in rats when given orally (Garg, 1974). Curcumin also inhibits human sperm motility and has the potential for the development of a novel intravaginal contraceptive (Ritha Porn *et al*., 2003).

Curcumin prevents galactose-induced cataract formation at very low doses. Both turmeric and curcumin decrease blood sugar level in aloxan-induced diabetes in rats (Suryanarayana *et al*., 2003).

Antimicrobial activity of curcumin, essential oil fraction, ether and chloroform extracts against bacteria such as *Streptococcus*, *Staphylococcus* and *Lactobacillus* and some dermatophytic fungi are reported (Banerjee and Nigam, 1978; Bhavani-Shankar and Sreenivasa-Murthy, 1979).

Though there has been much biomedical research on turmeric and curcuminoids, there have been few clinical trials. Rhizome powder of turmeric is used to treat wounds, bruises, inflated joints and sprains in Nepal (Surh, 2002). In the Indian system of medicine, it is used for the treatment of bilary disorders, anorexia, cough, diabetic wounds, hepatic disorders, rheumatism and sinusitis (Jain and De Fillips, 1991). Clinical and biochemical studies on the effect of turmeric (*C. longa*) on tissue repair after surgery in calves indicated the effect of turmeric in tissue repair and wound healing (Thugnaigat *et al*., 2000).

Aromatherapy and the perfume industry

Essential oil of turmeric in blends with other spice/herb oils is found to be effective in alleviating 'Pitta' and 'Kapha', 'doshas' in the Indian system of medicine (Marwah and Shetty, 2000). The essential oil of the dry leaf of *C. longa* is indicated as a potential oil for application in the perfumery, cosmetic and soap industry (Ramachandraiah *et al*., 1998).

Foods and food industry

Turmeric powder is used in mustard paste and curry powder to impart colour, aroma and taste. In Asian countries, whole dry or fresh turmeric, ground or turmeric powder with other spices is used for making vegetable and meat preparations and soups (Sasikumar, 2001). Turmeric powder mixed with sesame, coconut or groundnut oil is used for making mango, lime, gooseberry, garlic and other pickles (Govindarajan, 1980).

Apart from imparting colour and aroma to foods, another important corollary action of turmeric and curcuminoids is to prevent the oxidation and resultant rancidity of oils and fats during storage and heating through inhibition of the formation of harmful free radicals (Revarkar and Sen, 1975).

Turmeric oleoresin is used mainly in brine pickles (Eiserle, 1966; Cripps, 1967) and also to some extent in mayonnaise and relish formulations, in non-alcoholic beverages such as orangeades and lemonades, in gelatins, in breading of frozen fish sticks, in potato croquettes, in butter and cheese in the form of powder or granules for garnishing, and even in ice creams, mainly as a colouring material (Perotti, 1975).

Pure curcumin as such is not used by the food industry as it is insoluble in water and has poor solubility in other solvents. Hence, curcumin is dissolved in food-grade solvent and permitted emulsifier such as polysorbate 80 for converting into a convenient application form, which contains about 10% curcumin.

The colour in the Food Regulation Act 1996, Part III Schedule 5 specifies the limits of curcumin in various food items in the UK (Table 7) (Henry, 1998). The usual dose level of curcumin is in the range of 5–200 ppm. Numerous blends are available to suit the colour of the product. Vanilla ice cream, for example, is coloured with a combination of curcumin (200 ppm) and inorbixin (12 ppm). Similarly, in yoghurt 5 ppm curcumin will give an acceptable colour. For cakes and biscuits the required colour is achieved using a blend of curcumin (10–15 ppm) and annatto (10 ppm).

Ornamental

Curcuma alismatifolia, *C. thorelii* (Fig. 2) and *C. roscoeana* are the most important *Curcuma* species having ornamental value. *C. alismatifolia* is a relatively new cut flower crop that is becoming a favourite in the

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Table 7. Limits specified for curcumin in various food items (Colours in Food Regulations Act 1995 Schedule 5, Part III)

Food	Maximum level
Non-alcoholic flavoured drinks	100 mg/l
Candled fruits and vegetables *mostarda di frutta*	200 mg/kg
Preserves of red fruits	200 mg/kg
Confectionery	300 mg/kg
Decorations and coatings	500 mg/kg
Fine bakery wares (e.g. viennoiseric, biscuits, cakes and wafers)	200 mg/kg
Edible ices	150 mg/kg
Flavoured processed cheese	100 mg/kg
Desserts including flavoured milk products	150 mg/kg
Sauces, seasonings (for e.g. curry powder, tandoori pickles, relishes chutney and piccalilli)	500 mg/kg
Mustard	300 mg/kg
Fish paste and crustacean paste	100 mg/kg
Pre-cooked crustaceans	250 mg/kg
Salmon substitutes	500 mg/kg
Surimi	500 mg/kg
Fish roe	300 mg/kg
Smoked fish	100 mg/kg
'Snacks': dry, savoury potato, cereal or starch-based snack products; extruded or expanded savoury snack products	200 mg/kg
Edible cheese rind and edible casings	*Quantum satis*
Complete formulae for weight control intended to replace total daily food intake or an individual meal	50 mg/kg
Complete formulae and nutritional supplements for use under medical supervision	50 mg/kg
Liquid food supplements/dietary integrators	100 mg/kg
Solid food supplements/dietary integrators	300 mg/kg
Soups	50 mg/kg
Meat and fish analogues based on vegetable proteins	100 mg/kg
Spirituous beverages (including products less that 15% alcohol by volume), except any mentioned in Schedule 2 or 3	200 mg/l
Aromatized wines, aromatized wine-based drinks and aromatized wine product cocktails as mentioned in Regulation (EEC) No. 1601/91, except any mentioned in Schedule 2 or 3	200 mg/l
Fruit wines (still or sparkling), cider (except *cidre bouche*) and perry aromatized fruit wines, cider and perry	200 mg/l

Source: Henry (1998).

international market (Halevy, 1997a). Research work on micropropagation, vase life and storage condition as well as agronomic studies in *C. alismatifolia* are currently in full swing (Wannakrairoj, 1997; Halevy, 1997b; Chin Shing *et al.*, 1999).

Breeding and varieties

Turmerics, though propagated vegetatively, set viable seeds (Sasikumar *et al.*, 1994). Cultivated turmeric (*C. longa*) is a cross-pollinated, triploid species

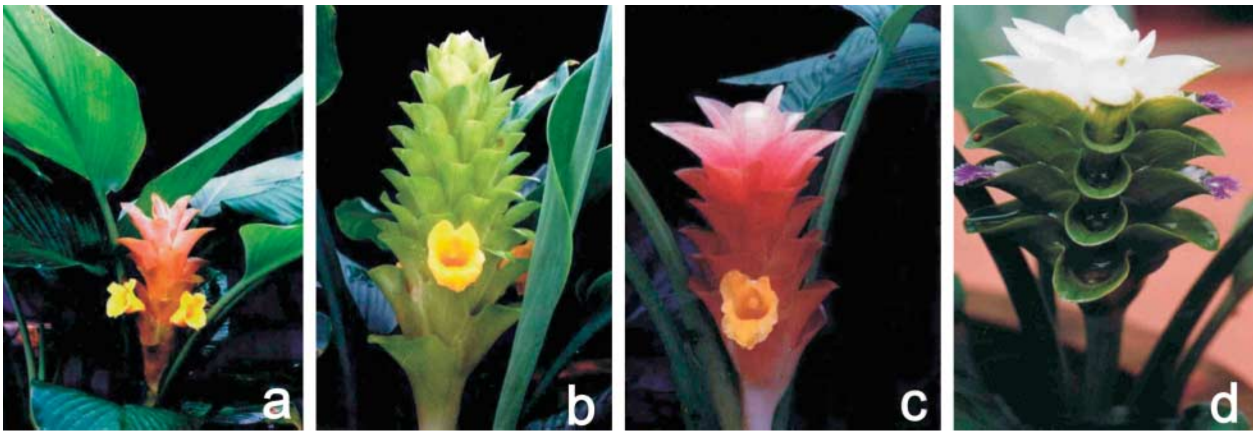

Fig. 2. Bract colour variation in *Curcuma ecalcarata* (a–c) and *C. thorelii* (d).

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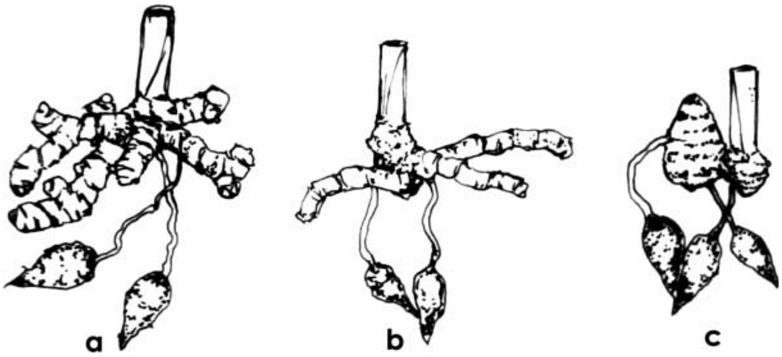

Fig. 3. Nature of rhizomes in *Curcuma*: (a) sessile tubers present; (b) stoloniferous; (c) sessile tubers absent.

$2n = 3x = 63$ (Nazeem and Menon, 1994). In the past, crop improvement in turmeric has been limited to germplasm selection, clonal selection and mutation breeding. But with the observation of viable seed set in turmeric, recombination breeding through hybridization and open-pollinated progeny (true turmeric seedlings) selection are also in progress now. 'Prabha' and 'Prathibha' are the first ever turmeric varieties evolved through open-pollinated progeny selections (Sasikumar *et al.*, 1996). All other improved Indian turmeric varieties are either germplasm selection or clonal selection barring the varieties Co-1, BSR-1 and BSR-2, which are mutant selections. 'Dimla' and 'Sinduri', the improved turmeric varieties of Bangladesh (Hoque, 1995), are also selections. There are about 50 land races/cultivars in addition to about 20 improved varieties of turmeric in India (Sasikumar *et al.*, 1999). Cultivar/varietal diversity of turmeric in India is given in Table 8.

The important breeding objectives in turmeric are high yield coupled with high dry recovery (above 15%), high curcumin (above 5%) and resistance to pests. The improved varieties are comparatively high yielding (20–40 t/ha) and good quality. Maturity of improved varieties is 6–9 months though there are some local types which mature within 6 months.

Turmeric is raised either as an irrigated or rainfed monocrop or intercrop. Crop improvement work in other *Curcuma* species is very meagre. Variety 'Amba' is the lone improved selection of *C. amada*.

Though turmeric is propagated using rhizome bits, tissue culture protocol for propagation is available in some of the *Curcuma* species (Nadagauda *et al.*, 1978; Balachandran *et al.*, 1990; Borthakur and Bordoloi, 1992; Sanghamitra and Nayak, 2000; Prakash *et al.*, 2004). However, tissue culture propagation of *Curcuma* is not cost effective or agronomically superior to rhizome propagation as a plantation practice.

Production, export and processing

India is the major producer and exporter of turmeric in the world. As a provisional estimate, India produced 528,000 Mt of turmeric from about 150,000 hectares during 2002–2003. During 2002–2003 India exported 32,400 Mt of turmeric worth US$23 million to different countries. Turmeric is exported as turmeric dry, turmeric powder, turmeric oil and turmeric oleoresin besides curry powder.

During 2002–2003, the United Arab Emirates topped the list of turmeric import from India (4724 Mt) followed by the USA (3914 Mt), Japan (2614 Mt), UK (2006 Mt), Malaysia (1993 Mt), Sri Lanka (1907 Mt), Netherlands (1742 Mt) and South Africa (1254 Mt).

The important regional trade varieties of turmeric from India are 'Rajapuri', 'Duggirala', 'Cuddappah', 'Berhampur', 'Erode', 'Nizamabad', 'Koraput', 'Kasturi', 'Chaya', 'Kodur', 'Salem', Waigon, Alleppey, Karur, Tekurpeta and others (Govindarajan, 1980). Besides

Table 8. Cultivar/varietal diversity of turmeric (*Curcuma longa*) in India

Cultivar/variety	Cultivar/variety	Cultivar/variety
Armur	Ethammukkala	Ranga[a]
Alleppey	Gorakpur	Rajapuri
Avanigadda	Guntur	Renuka
Amruthapani	GL Puram	Rasmi[a]
Amalapuram	Jabedi	Rajendra Sonia[a]
Balaga	Kasturi	Roma[a]
Bilaspur	Kanti[a]	Shimla
Bullapura	Kasturi Tanaka	Sobha[a]
BSR-1[a]	Katpadi Local	Sugandham[a]
BSR-2[a]	Krishna[a]	Suguna[a]
C-A-72 Udayagiri	Kothapetta	Suvarna[a]
C-A-12	Lekadong	Sudarshana[a]
CLL-324	Lokhande	Suranjana[a]
CLL-328	Mundage	Suroma[a]
Chinnanadan	Mydukkur	Thekkurpetta
Chayapaspu	Megha turmeric[a]	T Sundar
Co-1[a]	Nandyal	Talachira
Deshi	Pattani	Yelachira
Duggirala	Panamalur	Varna[a]
Dundrigam	Perumnadan	Vombinitta
Dughi	Prabha[a]	Vonimitta
Erode Local	Prathibha[a]	Wayanadan

[a] Improved variety.

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Indian turmeric, Chinese turmeric is also traded globally. However, as compared to the Chinese commodity, Indian turmeric is sold at a higher price internationally. The average annual spot price of Indian turmeric having 5.5% curcumin ('Alleppey' turmeric) in New York was 81.0 US cents/pound during 2003–2004. The figure for the Chinese produce for the corresponding year is not available. However, during 1992–1993 Indian turmeric ('Alleppey' turmeric) was sold at 94.0 US cents/pound and Chinese produce at 39.0 US cents/pound in New York. Though curcumin is a factor in deciding the price of turmeric, 'Rajapuri' turmeric from India, which is 3–4% curcumin, fetches a higher price in the domestic market than the best 'Alleppey' turmeric with 5.5% curcumin.

Harvested turmeric is washed well to remove the adhering soil and roots and separated into finger and mother rhizomes. Mother and finger rhizomes are boiled separately for about 40–60 min under slightly alkaline conditions (100 g of sodium bicarbonate or sodium carbonate in 100 litres of water) in copper, galvanized iron or earthen vessels and then sun-dried on bamboo mats or a clean drying floor for 10–15 days so as to bring down the moisture to 10–11%. Dry recovery of cured turmeric varies between 15 and 25% depending on varieties, location and cultural practices.

Another method of curing is by taking the cleaned mother and finger rhizomes (approximately 50 kg) separately in a perforated trough of convenient size made of galvanised iron or mild steel sheet with extended parallel handles. The troughs containing the fingers are immersed in a pan; 100 litres of water are poured into the pan to immerse the turmeric. The whole mass is boiled until it becomes soft. The rhizomes are then taken out and sun-dried. Dried turmeric is then polished either manually or mechanically in power-operated drums. Polished rhizomes are made more attractive by artificially colouring them with turmeric powder or emulsion. During polishing itself turmeric is added to the drums either as a powder or as emulsion. Processed turmeric is sorted as fingers, round, split or non-specified and marketed under its varietal name such as 'Rajapuri', 'Alleppey', 'Erode' and 'Duggirala' from India. The Indian 'Agmark' standards include separate grading for different varieties. 'Special', 'good' and 'fair' are some of the grade specifications. Govindarajan (1980) has given specification for Indian turmeric (whole or ground) (Table 9). The processed turmeric is stored in fresh jute bags or in sound clean, dry, heat-sealed polythene bags in dry, cool warehouses.

Turmeric powder is obtained by powdering the clean, dry, stone-hard fingers using a hammer mill followed by disc-type attrition mills to obtain 60–80 mesh powder. Powdered turmeric is packed in bulk containers such as fibre hard drums, multi wall bags and tin containers suitably lined or coated to prevent moisture absorption, loss of flavour and colour. For the retail trade, the unit package is in flexible packaging materials, such as low- and high-density polythene, polyvinyl chloride or glass packs.

Turmeric is valued mainly for curcuminoids, oleoresin and essential oil besides other nutritive constituents (Table 10). In pure form, curcuminoids separate as an orange-yellow crystalline powder, insoluble in water, slightly soluble in alcohol and glacial acetic acid. Curcuminoids are extracted from turmeric powder in alcohol or ethyl acetate for 2.5–3.0 h and crystallized using

Table 9. Indian specification for turmeric—grades

	Maximum weight (%)				
Grade designation	Pieces	Foreign matter	Defectives	Bulb	Characteristic
Fingers (general)					Finger-like shape; breaks with a metallic twang; well set and close grained; perfectly dry; free from damage from weevils; over boiling etc.
Special	2.0	1.0	0.5	2.0	
Good	3.0	1.5	1.0	3.0	
Fair	5.0	2.0	1.5	5.0	
Fingers ('Alleppey')					As above
Good	5.0	1.0	3.0	4.0	
Fair	7.0	1.5	5.0	5.0	
Finger ('Rajapuri')					As above; admixture of other *Curcuma* varieties allowed at a maximum of 2, 5 and 10% in the three grades, respectively.
Special	3.0	1.0	3.0	2.0	
Good	5.0	1.5	5.0	3.0	
Fair	7.0	2.0	7.0	5.0	
Bulbs (rounds)					Well-developed, smooth, sound, free from rootlets.
Special	–	1.0	1.0	–	
Good	–	1.5	3.0	–	The 'Rajapuri' variety has higher allowance of 3, 5 and 7% defectives in the three grades, respectively.
Fair	–	2.0	5.0	–	

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Table 10. Nutritional composition of turmeric

Constituent	Quality per 100 g
Water (g)	6.0
Food energy (kcal)	390
Protein (g)	8.5
Fat (g)	8.9
Carbohydrate (g)	69.9
Ash (g)	6.8
Calcium (g)	0.2
Phosphorus (mg)	26
Sodium (mg)	0.03
Potassium (mg)	2
Iron (g)	47.5
Thiamine (mg)	0.09
Riboflavin (mg)	0.19
Niacin (mg)	4.8
Ascorbic acid (mg)	50

Source: Peter (1999).

non-polar solvents such as benzene and purified further (limits specified for curcumin in various food items are presented in Table 7).

Turmeric oleoresin is orange-red in colour and consists of an upper oily layer and a lower crystalline layer (Krishnamurthy *et al.*, 1976). For commercial use, it is usually mixed with non-volatile edible solvents such as vegetable oil, propylene glycol or polyethylene sorbitan fatty acid esters in order to disperse the extracted material and render it free flowing and soluble (Purseglove *et al.*, 1981). Turmeric oleoresin is obtained by solvent extraction of ground turmeric. Acetone is a good solvent for extracting oleoresin. Soxhlet apparatus or cold percolation is used for extraction. Curcumin, the principal colouring matter, forms about one-third of a good-quality oleoresin. Yield of oleoresin varies from 7 to 15% depending on varieties, location and cultivation practices.

Turmeric rhizome contains 3–5% essential oil, which is obtained by steam distillation of turmeric powder for 8–10 h. It is a pale yellow-coloured liquid with peppery and aromatic odour. The main component of turmeric oil is turmeron.

Turmeric powder is the major component (40–50%) of curry powder, a spice mix used for seasoning dishes containing vegetables, meat, fish, egg or vegetable plus meat or fish in the Orient. In the West also curry powder is used for seasoning dishes. Turmeric powder imparts colour and background aroma to the curry powder.

Conclusion

Curcuma is a rare genus having diverse uses in fields such as religion, medicine, aromatherapy, cosmetics, dye, floriculture and of course the food industry. Molecular taxonomic studies initiated recently, taken in conjunction with morpho-taxonomic parameters, may resolve the identity of various closely resembling *Curcuma* species when there is confusion with respect to their unequivocal identity. As curcumin is now gaining importance all over the world as a potential source of new drugs to combat a variety of ailments, the exact taxonomic characterization is very significant from the bio-prospecting angle. Curcuminoids, extracts of turmeric in various solvents and essential oil derived from different *Curcuma* species are the molecules responsible for the biological activity of turmeric. Though there is fair knowledge about the essential oil profile of some of the *Curcuma* species, the profile of curcuminoids in the different *Curcuma* species and within the varieties of *C. longa* is yet to be studied in detail. There is urgent need to pay due attention to qualitative and quantitative differentiation of curcuminoids, since the proportion of different curcuminoids will be a critical factor in the biomedical activity of *Curcuma* and, in future, turmeric may be priced based on the levels of the curcuminoids. Future turmeric varieties may also be bred specifically for particular curcuminoids or the essential oil constituents. Viable sexual reproduction coupled with excellent vegetative propagation methods make such breeding easier. Molecular markers linked to particular constituents are an area of virgin research in the genus. Elucidation of the biosynthetic pathway of curcuminoids and identification of the key enzymes involved will pave the way for more biotechnological manipulations besides forming screening criteria for the sexually derived true turmeric seedlings.

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