RESEARCH PAPER

Cucumis callosus—A Neglected Cucurbit of the Indian Subcontinent: Taxonomy, Phytochemistry, Health Benefits, and Value Addition: A Review

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ABSTRACT
Underutilized and neglected crops are increasingly recognized for their potential to enhance food and nutritional security, particularly under conditions of climate change, agrobiodiversity loss, and rising prevalence of non-communicable diseases. *Cucumis callosus* (Rottler) Cogn., commonly known as kachri or wild melon, is a traditionally important yet scientifically underexploited cucurbitaceous species native to the Indian subcontinent. Widely distributed across arid and semi-arid regions of India, *C. callosus* exhibits remarkable adaptation to high temperatures, low and erratic rainfall, and nutrient-poor soils, making it a promising climate-resilient crop. This review provides a comprehensive synthesis of existing literature on the taxonomy, morphology, distribution, agro-ecological adaptation, genetic diversity, and gene-pool relationships of *C. callosus*, highlighting its close phylogenetic affinity with cultivated melon (*Cucumis melo* L.). The nutritional profile of the species reveals appreciable levels of dietary fiber, essential minerals, antioxidant vitamins, and bioactive lipids while phytochemical investigations identify cucurbitacins, phenolic compounds, flavonoids, carotenoids, and tocopherols as major bioactive constituents. Pharmacological studies substantiate several traditional claims, demonstrating antioxidant, antidiabetic, antihyperlipidaemic, anti-inflammatory, antimicrobial, and anticancer activities. The review further examines traditional and modern post-harvest processing, drying, irradiation, and value-addition practices, emphasizing their role in reducing losses and improving shelf life. Despite its multifaceted potential, limitations such as inadequate agronomic standardization, limited toxicological data, fragmented value chains, and insufficient policy support hinder wider utilization. Addressing these gaps through interdisciplinary research, conservation, and commercialization strategies can enable *C. callosus* to contribute meaningfully to sustainable food systems, functional foods, and climate-smart agriculture.

Keywords: *Cucumis callosus*; underutilized crops; functional foods; phytochemicals; climate-resilient agriculture; nutraceuticals; value addition

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INTRODUCTION

Underutilized and neglected crops are increasingly recognized as critical components of resilient and eco-friendly food systems, particularly in the context of climate change, nutritional insecurity, and declining agrobiodiversity (Karunaratne et al., 2024). Although more than 7,000 plant species have historically contributed to human diets, modern agriculture relies heavily on a limited number of crops, resulting in increased vulnerability of food systems and nutritional monotony(Raneri et al., 2023). These challenges are further intensified in dry and semi-dry regions due to erratic rainfall, rising temperatures, soil degradation, and limited irrigation infrastructure, necessitating the identification and promotion of climate-resilient indigenous plant resources(Manoharan et al., 2025). Globally, NCDs account for nearly 71% of deaths, with a disproportionately greater burden in low- and middle-income countries, emphasizing the need for diet-based preventive strategies. (Jailobaeva et al., 2021).

India, despite being one of the world's leading producers of fruits and vegetables, continues to face regional disparities in nutritional security, particularly in drought-prone and resource-poor agro-ecosystems

(Shahid, 2025). Indigenous crops adapted to harsh environmental conditions offer viable solutions because of their resilience, low input requirements, and cultural acceptability, while supporting sustainable livelihoods and ecological stability (Karunaratne et al., 2024).

In this context, *Cucumis callosus* (Rottler) Cogn., commonly known as kachri, wild melon, or bitter cucumber, represents a traditionally important yet scientifically underutilized cucurbitaceous species native to the Indian subcontinent (Pessarakli, 2016). Indigenous consumption patterns, resilience to harsh climatic conditions, and emerging evidence of pharmacological potential position *C. callosus* as a promising functional food resource (Deepika et al., 2023).

Cucumis callosus is widely distributed across the water-scarce and semi-water-scarce regions of Rajasthan, Gujarat, Madhya Pradesh, Haryana, Maharashtra, Karnataka, and parts of southern India, where it grows naturally in sandy soils, wastelands, scrublands, fallow lands, and rain-fed agricultural margins (Pessarakli, 2016; Gadekar, 2023; Boora et al., 2025). The species is naturally adapted to high temperatures, low and erratic rainfall, and poor soil fertility, underscoring its ecological significance and potential role in climate-smart agriculture under projected global warming scenarios(Manoharan et al., 2025; Vaghasiya & Ishnava, 2024).

Traditionally, kachri fruits are consumed fresh or after drying and constitute an essential component of indigenous diets in hot arid regions of India (Pessarakli, 2016). Dried kachri is a key ingredient of the traditional Rajasthani dish *Panchkuta*, prepared along with other desert-adapted species such as *Capparis decidua* (ker), *Prosopis cineraria* (sangri), *Cordia dichotoma* (gunda), and *Citrullus colocynthis* (kumti) (Boora et al., 2025; Goyal & Sharma, 2009). In addition, the fruits are used in chutneys, pickles, spice blends, digestive formulations, mouth fresheners, and as a souring agent in regional cuisines(Choudhary et al., 2023; Vaghasiya & Ishnava, 2024). One of the most distinctive culinary applications of *C. callosus* is its use as a natural meat tenderizer, attributed to the presence of proteolytic enzymes capable of improving the texture and palatability of tough meats (Deepika et al., 2023; Boora et al., 2025).

Beyond its culinary value, *Cucumis callosus* holds substantial ethnomedicinal importance. Ethnobotanical surveys across Rajasthan, Gujarat, Odisha, and parts of southern India document the use of its fruits, seeds, flowers, and roots for managing digestive disorders, diabetes, urinary ailments, heat stress, skin infections, and inflammatory conditions (Gadekar, 2023; Deepika et al., 2023). According to Ayurveda, the fruit pulp of *Cucumis callosus* is described as bitter and acrid in taste and is considered thermogenic, anthelmintic, hepatoprotective, cardioprotective, appetizing, expectorant, and intellect-promoting, while the roots are traditionally used as emetic and purgative agents. Such indigenous knowledge systems have evolved through generations and provide an important foundation for functional food and nutraceutical development when supported by modern scientific validation (Heinrich et al., 2017).

Recent phytochemical and pharmacological investigations have begun to scientifically substantiate several traditional claims associated with *C. callosus*. Extracts derived from fruits and seeds have demonstrated antioxidant, antidiabetic, anti-inflammatory, antihyperlipidaemic, antimicrobial, and anticancer activities in vitro and in preclinical models (Panda et al., 2018; Deepika et al., 2023; Deepika et al., 2024). These biological effects are primarily associated with the presence of cucurbitacins, flavonoids, phenolic compounds, carotenoids, vitamins, and essential fatty acids, positioning *C. callosus* as a promising functional food and nutraceutical resource (Gadekar, 2023).

From an evolutionary and genetic perspective, *Cucumis callosus* has gained renewed scientific attention due to its close phylogenetic relationship with cultivated melon (*Cucumis melo* L.). Modern molecular phylogenetic and population genomic studies have identified Indian wild melon populations, including *C. callosus*, as part of the primary gene pool of cultivated melon and as important contributors to melon domestication and diversification (Endl et al., 2018; Pandey et al., 2021; Zhao et al., 2021). These studies have also emphasized its potential as a bank of genes that confer resistance to drought, tolerance to heat stress, pest resistance, and adaptation to marginal environments, which will eventually assume greater significance for crop improvement under scenarios of climate change (Pandey et al., 2021; Zhao et al., 2021).

Despite its multifaceted importance, *Cucumis callosus* remains poorly integrated into formal agricultural systems, food processing industries, and nutraceutical value chains. High post-harvest losses, lack of standardized cultivation and processing protocols, limited consumer awareness, erosion of traditional knowledge, and insufficient policy support have collectively restricted its wider utilization (Mmbando, 2025; Onomu, 2023). Furthermore, existing scientific literature on the species remains fragmented across disciplines, with limited synthesis of botanical, nutritional, genomic, and pharmacological information.

In view of these considerations, the present review critically compiles and synthesizes updated scientific literature on the taxonomy, morphology, distribution, agro-ecological adaptation, genetic diversity, nutritional composition, phytochemical profile, pharmacological properties, post-harvest processing, and value-addition potential of *Cucumis callosus*. The review also identifies key knowledge gaps and future research directions required for its sustainable utilization, conservation, and commercialization as a climate-resilient functional crop.

2. Botanical Description and Morphological Characteristics of *Cucumis callosus*

Cucumis callosus (Rottler) Cogn. is a drought-adapted cucurbitaceous species exhibiting a suite of morphological traits that enable survival, growth, and reproduction under arid and semi-arid environmental conditions. The species is typically annual to short-lived perennial in habit and displays a prostrate to climbing growth form, spreading extensively across the soil surface or over surrounding vegetation with the help of axillary tendrils (DEEPIKA et al., 2023; Křístková et al., 2003). This growth behavior enhances ground coverage and reduces soil moisture loss(Jahantigh & Jahantigh, 2023) while improving competitive ability in nutrient-poor and high-temperature environments(Tesfay et al., 2023).

Cucumis callosus is a drought-adapted cucurbit exhibiting a prostrate to climbing growth habit with extensive branching and pubescent stems, features that reduce transpiration and heat stress under arid conditions (Swamy, 2017). Leaves are palmately lobed with dense trichomes, enhancing thermal regulation(Bickford, 2016), while tendrils facilitate climbing and light interception(Hong et al., 2023; Paul & Yavitt, 2010). Table 1 presents the botanical and agronomic characteristics of *Cucumis callosus* (Rottler) Cogn., an underutilized cucurbit adapted to dry and semi-dry regions, highlighting its growth habit, reproductive nature, edible parts, and tolerance to abiotic stresses. The general growth habit of *Cucumis callosus*, illustrating its prostrate to climbing vine nature with lobed leaves and axillary tendrils, is shown in Figure 1.

Figure 1. Growth habit of *Cucumis callosus* (Rottler) Cogn. showing prostrate to climbing vine, palmately lobed leaves, axillary tendrils, and yellow flowers under field conditions

Parameter	Description
Scientific name	*Cucumis callosus* (Rottler) Cogn.
Family	Cucurbitaceae
Common names	Kachri, Wild melon, Bitter cucumber
Growth habit	Prostrate or climbing vine
Reproductive nature	Monoecious
Growing season	Kharif and summer
Agro-ecological zone	Arid and semi-arid regions
Edible parts	Fruits, seeds, roots, leaves
Edible part sold	Fresh fruits/ Dehydrated fruits/slice
Farmer's market price per Kg (Rs.)	18-45
Utilisation and consumption forms	Preparation and vegetables (pure and mixed both), dehydrated slice/pieces/whole fruit (Kachri goite), pickle, fried chutney, dry chutney, powder, juice, hajmola, squash, jam, papadi, spices mouth freshener.
Stress tolerance	Drought, high temperature, poor soils

Table 1. Botanical, agronomic profile and utilization pattern by the farmers of *Cucumis callosus*. Data compiled from: Chakravarty (1982); Pessarakli (2016); Meena et al., (2016).

2.1 Vegetative morphology

The stem of *C. callosus* is slender, angular, and longitudinally ridged, bearing dense, coarse trichomes that impart a rough and scabrous texture. Stem pubescence is considered an adaptive feature that reduces transpiration(Cocoletzi et al., 2019), reflects excessive solar radiation(Chen et al., 2022), and provides protection against herbivory(Kaur et al., 2023). Similar roles of trichomes have been documented in other arid-adapted cucurbits and desert plants, where pubescence contributes to thermoregulation and drought tolerance (Bickford, 2016; Chen et al., 2022).

Leaves are alternate, simple, and broadly ovate to cordate, typically measuring 5–15 cm in both length and width. The lamina is palmately lobed, usually with three to five lobes, although considerable intraspecific variation has been reported among wild populations (Endl et al., 2018). Leaf surfaces are rough and densely hairy(Winter, 1990), while long petioles elevate the lamina above the soil surface, optimizing light interception under high irradiance conditions(Peil et al., 2002; Rouini et al., 2025). The presence of thick cuticles and dense trichomes further contributes to reduced water loss and enhanced tolerance to heat and drought stress (Jolliffe et al., 2023; Liu et al., 2022).

Tendrils arise from the leaf axils and are slender, spirally coiled, and either unbranched or bifurcate(Křístková et al., 2003; Winter, 1990). These tendrils allow the plant to climb adjacent vegetation or supports, thereby improving access to light and enhancing reproductive success in competitive habitats. Tendril-assisted climbing is a characteristic feature of the Cucurbitaceae and has been associated with improved photosynthetic efficiency and yield stability (Schaefer & Renner, 2011).

2.2 Reproductive morphology

Cucumis callosus is monoecious, bearing separate staminate (male) and pistillate (female) flowers on the same plant. Flowers are solitary or occur in small axillary clusters and are actinomorphic, pentamerous, and bright yellow in color—features typical of the genus *Cucumis* (Sebastian et al., 2010; Endl et al., 2018).

Male flowers typically appear in clusters comprising three to five and possess three stamens with sinuous anthers, while female flowers are typically solitary or paired and are distinguished by the presence of an inferior ovary densely covered with trichomes (Sebastian et al., 2010). Pollination is predominantly entomophilous, with bees serving as the primary pollinators(Knapp & Osborne, 2019). Flowering, fruit set, and seed development are strongly influenced by temperature, photoperiod, and soil moisture availability, with peak flowering commonly occurring during favorable post-monsoon conditions (Free, 1970; Gadekar, 2023).

2.3 Fruit morphology and characteristics

The fruit of *C. callosus* is a typical cucurbit pepo, small to medium in size, ovoid to ellipsoid in shape, and generally measuring 4–7 cm in length. Fruit weight varies widely depending on genotype and environmental conditions, ranging from approximately 50 to 200 g (Pessarakli, 2016; Boora et al., 2025).

The fruit surface is rough and often warty, serving as a distinguishing morphological feature that differentiates *C. callosus* from many cultivated melon (*C. melo*) varieties (Boora et al., 2025). The fruit pulp is thin, pale yellow to orange, and surrounds a large central seed cavity. The fruit contains a large seed cavity and is initially bitter, developing sweetness upon ripening (Pitrat, 2016). Immature fruits are characteristically bitter due to high concentrations of cucurbitacins, which act as chemical deterrents against herbivores. As fruits mature, bitterness decreases, and a mildly sweet to acidic flavor develops, increasing their suitability for culinary and processing applications (Deepika et al., 2023; Deepika et al., 2024). The external morphology of the fruit, longitudinal section showing pulp and seed cavity, and characteristic seeds of Cucumis callosus are illustrated in Figure 2.

Figure 2. Fruit morphology of *Cucumis callosus* showing whole mature fruit, longitudinal section revealing pulp and seed cavity, and characteristic flattened seeds.

2.4 Seed and root system

Seeds of *C. callosus* are flattened, oblong to elliptic, creamy white to pale brown, and measure approximately 6–10 mm in length. They are embedded in a mucilaginous matrix and exhibit notable nutritional value, containing proteins, lipids, vitamin E, and essential fatty acids, including omega-3 fatty acids (Gupta et al., 2021). The root system is fibrous and moderately deep, enabling efficient exploitation of subsurface soil moisture. This rooting pattern, combined with rapid vegetative growth and stress-responsive physiology, allows *C. callosus* to survive extended dry periods characteristic of arid and semi-arid ecosystems (Chaves et al., 2016; Endl et al., 2018).

2.5 Morphological variability and adaptive significance

Substantial morphological variability exists among *C. callosus* populations with respect to leaf lobing, fruit size, rind texture, bitterness intensity, and growth habit. This variability reflects long-term adaptation to heterogeneous environments and indicates considerable genetic diversity within the species (Endl et al., 2018; Pandey et al., 2021). Recent studies suggest that such phenotypic diversity may serve as a valuable resource for selecting stress-tolerant genotypes in cucurbit breeding programs aimed at enhancing climate resilience. Traits such as pubescence density, fruit bitterness, and growth habit may function as adaptive markers linked to drought tolerance and environmental fitness (Zhao et al., 2021).

3. Taxonomy, Origin, and Gene Pool Relationship of *Cucumis callosus*

3.1 Taxonomic position and systematic status

Cucumis callosus (Rottler) Cogn. belongs to the family Cucurbitaceae and the genus *Cucumis* L., which comprises more than 50 species distributed primarily across Africa and Asia. The genus includes economically important crops such as cucumber (*Cucumis sativus* L.) and melon (*Cucumis melo* L.). Africa is recognized as the primary center of diversity for the genus, while Asia represents a secondary center of diversification for melon-related taxa (Schaefer & Renner, 2011; Endl et al., 2018).

The taxonomic status of *C. callosus* has historically been contentious due to its close morphological similarity and reproductive compatibility with cultivated melon. Earlier floristic treatments and taxonomic accounts often described it as a wild or feral form of melon, assigning it varietal or subspecific status under *C. melo*, such as *Cucumis melo* var. *callosus* Rottler, *Cucumis trigonus* Roxb., and *Cucumis pseudocolocynthis* Royle (Sebastian et al., 2010; Endl et al., 2018). These classifications were primarily based on morphological descriptors, including fruit size, bitterness, and rind texture(Hua et al., 2019; Omari et al., 2018).

With the advent of molecular systematics, taxonomic interpretations of *C. callosus* have undergone significant refinement. Contemporary taxonomic consensus increasingly recognizes *C. callosus* as a distinct wild taxon within the *C. melo* species complex, characterized by unique ecological adaptation and genetic signatures shaped by long-term selection under arid Indian environments (Endl et al., 2018; Zhao et al., 2021).

3.2 Molecular phylogeny and species delimitation

Early molecular phylogenetic studies using chloroplast DNA (cpDNA) regions and nuclear ribosomal internal transcribed spacer (ITS) sequences revealed that Indian wild melons, including *C. callosus*, cluster closely with cultivated melon rather than with African *Cucumis* species (Sebastian et al., 2010; Schaefer & Renner, 2011). These findings suggested an Asian lineage within the broader *Cucumis* radiation and provided initial molecular support for the close evolutionary affinity between *C. callosus* and *C. melo*.

Subsequent studies employing higher-resolution molecular markers, including simple sequence repeats (SSRs), amplified fragment length polymorphisms (AFLPs), and single nucleotide polymorphisms (SNPs), consistently demonstrated low genetic distance and strong genomic synteny between *C. callosus* and cultivated melon (Dhillon et al., 2007; Endl et al., 2018). These results confirmed that *C. callosus* falls within the *C. melo* clade rather than representing a distantly related species.

3.3 Population genomics and domestication insights

Advances in next-generation sequencing and population genomics have substantially improved understanding of the domestication history and gene pool structure of melon(Nimmakayala et al., 2016; Pavan et al., 2017). Large-scale resequencing studies and genome-wide SNP analyses have revealed that Indian wild melon populations, including *C. callosus*, harbor high allelic diversity and ancestral haplotypes that are absent or rare in modern cultivated melons (Pandey et al., 2021; Zhao et al., 2021).

Zhao et al. (2021), through comprehensive genome variation mapping of global melon accessions, demonstrated that South Asian wild melons form basal lineages within the *C. melo* phylogeny. These findings support a polycentric domestication model in which Indian wild forms, including *C. callosus*, contributed genetically to the domestication and diversification of cultivated melon.

Genomic regions associated with fruit development, stress tolerance, and disease resistance exhibited strong signatures of selection, indicating historical gene flow between wild and cultivated populations(Liu et al., 2023; Marrano et al., 2018). Importantly, several drought- and heat-responsive genes enriched in wild Indian accessions were found to be underrepresented or lost in elite cultivated melons, highlighting the evolutionary and breeding value of *C. callosus* as a genetic reservoir (Pandey et al., 2021; Zhao et al., 2021).

3.4 Origin and center of diversity

Cucumis callosus is indigenous to the Indian subcontinent, with northwestern and central India—particularly Rajasthan, Haryana, Gujarat, Madhya Pradesh, and adjoining semi-arid regions—considered its primary center of occurrence and diversification (Pessarakli, 2016; Gadekar, 2023). The species thrives in environments characterized by high temperatures, low annual rainfall (approximately 250–800 mm), and nutrient-poor sandy or rocky soils(Vaghasiya & Ishnava, 2024).

Ethnobotanical continuity, widespread feral populations, and pronounced morphological variability across agro-ecological gradients suggest a long evolutionary history of *C. callosus* within the Indian subcontinent. Population genetic studies indicate that Indian wild melons possess significantly higher genetic diversity than many cultivated melon groups, reinforcing India's role as an important secondary center of diversification for the *C. melo* complex (Pandey et al., 2021; Zhao et al., 2021).

3.5 Gene pool classification and cross-compatibility with cultivated melon

Based on Harlan and de Wet's gene pool concept and supported by extensive experimental and molecular evidence, *Cucumis callosus* is classified within the primary gene pool (GP-1) of cultivated melon (*Cucumis melo* L.). This classification is supported by the following observations (John et al., 2012; Sabato et al., 2017; Sebastian et al., 2010).

- Complete sexual compatibility between *C. callosus* and *C. melo*

- Production of viable and fertile F_1 and backcross progenies
- Shared chromosome number (2n = 24)
- High genome synteny and low genetic divergence

Molecular marker studies further confirm extensive gene flow potential between wild *C. callosus* populations and cultivated melons. Traits of agronomic importance—such as drought tolerance, heat resilience, pest and disease resistance, and adaptation to low-input systems—are particularly enriched in *C. callosus*, making it an invaluable donor for melon improvement programs (Pandey et al., 2021; Boora et al., 2025).

3.6 Breeding significance and evolutionary implications

The recognition of *C. callosus* as a primary gene pool species has major implications for cucurbit breeding and climate-resilient agriculture. As modern melon cultivars face genetic erosion and increasing vulnerability to abiotic stresses, introgression of adaptive alleles from *C. callosus* offers a sustainable pathway for crop improvement using conventional, marker-assisted, and genomics-assisted breeding approaches (Endl et al., 2018; Zhao et al., 2021). From an evolutionary perspective, *C. callosus* provides a valuable living model for studying early domestication processes, feralization, and adaptive divergence within the *Cucumis* lineage. Its conservation and strategic utilization are therefore essential not only for crop improvement but also for understanding plant evolution under environmental stress(Parvathi et al., 2022; Wang et al., 2023).

4. Distribution, Agro-Ecological Adaptation, and Environmental Resilience of *Cucumis callosus*

4.1 Geographic distribution

Cucumis callosus is widely distributed across the arid and semi-arid regions of the Indian subcontinent. In India, the species occurs predominantly in Rajasthan, Gujarat, Haryana, Madhya Pradesh, Maharashtra, Karnataka, Tamil Nadu, and parts of the Deccan Plateau(DEEPIKA et al., 2023; John et al., 2012, 2018). Outside India, its occurrence has been reported in Pakistan, Nepal, Bangladesh, and Sri Lanka, primarily in regions characterized by low and erratic rainfall, high temperatures, and marginal soils(Ahmed et al., 2022; Liu et al., 2026; Srinivasarao et al., 2023).

Within these regions, *C. callosus* grows as a wild, feral, or semi-domesticated species and is commonly encountered along roadsides, fallow lands, wastelands, scrublands, field boundaries, and rain-fed agricultural margins (Pessarakli, 2016). Its frequent co-occurrence with cultivated melon fields further supports its long-term integration within traditional agro-ecosystems and the possibility of historical gene flow between wild and cultivated populations (Endl et al., 2018).

4.2 Habitat preference and ecological niche

Cucumis callosus exhibits remarkable ecological plasticity, allowing it to thrive in diverse yet harsh environments. The species shows a strong preference for:

- Sandy to loamy soils with low organic matter
- Well-drained substrates, including rocky and gravelly terrains
- Soil conditions ranging from slightly alkaline to moderately saline
- Open habitats with high solar radiation

Its minimal water requirement underscores its suitability for drought-prone agro-ecological zones.

4.3 Adaptation to arid and semi-arid environments

The success of *C. callosus* in arid landscapes is attributed to a combination of morphological, physiological, and phenological adaptations. *Cucumis callosus* is essentially a warm-season crop, and it requires a prolonged period of warm and humid climatic conditions for its optimal growth and development (Kirtikar et al., 1984). Dense pubescence on stems and leaves reduces transpiration, reflects excessive solar radiation, and protects tissues from heat and ultraviolet stress (Pessarakli, 2016).

Physiologically, *C. callosus* exhibits efficient water-use strategies, including rapid stomatal regulation, tolerance to transient water stress, and maintenance of cellular turgor under dehydration conditions.

Such synchronization with rainfall events represents a key adaptive strategy for persistence in these ecosystems (Gadekar, 2023).

The arid region soils where kachri grows are low in organic matter and available plant nutrients(Jatav et al., 2016). In these regions, nutrient use efficiency of kachri is generally low due to poor soil fertility, high temperature stress, and limited soil moisture availability, which restrict nutrient uptake and utilization efficiency (Jatav et al., 2016).

4.4 Genomic and molecular basis of stress tolerance

Recent advances in melon genomics provide compelling evidence that wild melon relatives, including *C. callosus*, possess enriched genetic architectures for abiotic stress tolerance.

Key gene categories implicated include:

- Abscisic acid (ABA) signaling genes, regulating stomatal closure and osmotic balance

- Heat-shock proteins (HSPs), protecting cellular proteins during thermal stress
- Reactive oxygen species (ROS) scavenging enzymes, including superoxide dismutase, catalase, and peroxidases
- Aquaporins and osmoprotectant-related genes, facilitating efficient water transport and cellular hydration

Comparative analyses indicate that many of these genes show stronger stress-induced expression and greater allelic diversity in wild accessions such as *C. callosus* than in domesticated melon cultivars, suggesting selective loss of adaptive alleles during domestication (Pandey et al., 2021; Zhao et al., 2021).

4.5 Transcriptomic responses and genotype–environment interactions

These transcription factors orchestrate downstream stress-response pathways that enhance dehydration tolerance, thermal resilience, and oxidative stress mitigation (Pandey et al., 2021).

Field observations and population genetic studies further indicate significant genotype–environment interactions in *C. callosus*, reflected in regional variation in fruit size, bitterness, phenology, and stress tolerance. Genomic signatures of local adaptation—such as allele frequency shifts in stress-related loci—have been detected in wild melon populations inhabiting contrasting agro-ecological zones (Zhao et al., 2021). This adaptive differentiation underscores the importance of conserving geographically diverse populations.

4.6 Ecological significance and ecosystem services

Beyond its agronomic value, *Cucumis callosus* plays an important ecological role in arid ecosystems. As a pioneer species, it colonizes degraded and nutrient-poor soils, contributing to soil stabilization and reduction of wind erosion—an essential ecosystem service in desert and semi-desert regions (Gadekar, 2023). The extensive ground coverage provided by its vines reduces surface evaporation and improves soil microclimate. Additionally, *C. callosus* supports local biodiversity by providing nectar resources for pollinators such as bees during periods when floral diversity is limited. Rapid biomass accumulation during favorable growth periods also contributes to carbon sequestration in degraded landscapes (Gadekar, 2023).

4.7 Relevance to climate-smart agriculture

In the context of climate change, increasing temperatures, water scarcity, and land degradation pose serious threats to conventional horticultural crops. Under such scenarios, *Cucumis callosus* emerges as a promising candidate for climate-smart agriculture. Its ability to produce edible and nutritionally valuable fruits under minimal inputs aligns with the principles of sustainable intensification and agro-ecological resilience (Chivenge et al., 2015).

Moreover, as a wild relative within the primary gene pool of melon, *C. callosus* represents a critical genetic reservoir for improving stress tolerance and adaptive traits in cultivated cucurbits. Conservation, characterization, and genomics-assisted utilization of its natural populations are therefore essential for safeguarding future food and nutritional security in arid and semi-arid regions(Boora et al., 2025).

5. Nutritional Composition, Physico-Chemical Properties, and Nutritional Significance of *Cucumis callosus*

5.1 Proximate composition

The fruits of *Cucumis callosus* are characterized by high moisture content, ranging from approximately 80.3% to 97.5%, which contributes to their refreshing nature and suitability for consumption in hot arid climates (Dahot et al., 1999; Pandey et al., 2021; Deepika et al., 2023). Despite high moisture levels, the fruits contain appreciable quantities of macronutrients and dietary fiber, making them nutritionally valuable components of traditional diets in arid regions(Boora et al., 2025). *Cucumis callosus* fruits are characterized by a high moisture content of approximately 88.99%, along with protein levels ranging from 2.16% to 3.67%, starch content of about 3.50%, crude fat at 0.482%, and dietary fiber around 4.12%. In addition, the seeds are a source of vitamin E and omega-3 fatty acids, further enhancing the nutritional value of the species (Manchali et al., 2021). The overall proximate and micronutrient composition of Cucumis callosus fruits, expressed on a fresh weight basis, is summarized in Table 2.

Component	Content
Moisture (%)	80.3–97.5
Protein (%)	2.16–3.67
Crude fat (%)	0.06–0.48
Dietary fiber (%)	2.87–4.12
Ash (%)	Up to 3.05
Iron (mg)	Up to 4.06
Zinc (mg)	Up to 1.49
Ascorbic acid (mg)	6.57–25.9
Total phenols (%)	9.15–29.5

Table 2. Proximate and micronutrient composition of *Cucumis callosus* fruits (per 100 g fresh weight). Source: Deepika et al., (2023); Boora et al. (2025).

Protein content in *C. callosus* fruits varies depending on genotype, maturity stage, and agro-ecological conditions, with reported values ranging from 2.16% to 3.67% on a fresh weight basis (Dahot et al., 1999). This protein content is notably higher than that reported for several other wild cucurbits and contributes to dietary protein intake in communities with limited access to animal protein sources(Attar & Ghane, 2021).

Crude fat content in the fruit pulp is relatively low, generally below 0.5%, which aligns with the low-calorie nature of the fruit and supports its suitability for inclusion in diets aimed at weight management and metabolic health (Pandey et al., 2021). Ash content, an indicator of total mineral matter, ranges from approximately 0.49% to 3.06%, reflecting variability in mineral accumulation among different accessions and growing environments (Dahot et al., 1999).

Dietary fiber content in *C. callosus* fruits ranges from 2.00% to 4.12%, with choti kachri consistently exhibiting higher fiber levels compared to badi kachri and snap melon types (Pandey et al., 2021; Boora et al., 2025). High fiber intake is associated with improved gastrointestinal health, glycemic regulation, and reduced risk of chronic metabolic disorders, further supporting the functional food potential of *C. callosus*. A comparative evaluation of the proximate composition, mineral content, antioxidant constituents, and moisture levels of choti kachri, badi kachri, and snap melon is presented in Table 3.

Parameter	Description
Scientific name	*Cucumis callosus* (Rottler) Cogn.
Family	Cucurbitaceae
Common names	Kachri, Wild melon, Bitter cucumber

	CHOTI KACHRI	BADI KACHRI	SNAP MELON
TSS (%)	0.639	0.592	0.480
Proteins (%)	2.16–3.67	0.220	0.288
Ash content (%)	3.059	0.570	0.494
Crude fat (%)	0.482	0.06	0.135
Dietary fiber (%)	4.12	2.87	2.00
Starch content (%)	3.50	1.20	1.17
Iron (mg/100 g)	4.06	0.207	0.250
Zinc (mg/100 g)	1.498	0.064	0.015
Total phenols (%)	29.5	9.15	37.9
Ascorbic acid (mg/100 g)	25.9	6.57	7.60
Moisture content (%)	80.3	97.5	97.0

TABLE 3: Comparative analysis among Choti kachri, Badi kachri, and snap melon. Source: Pandey et al., (2021)

5.2 Carbohydrates, sugars, and starch

The carbohydrate fraction of *C. callosus* fruits is composed primarily of simple sugars, structural polysaccharides, and modest amounts of starch. Total soluble solids (TSS) values reported for different kachri types range from approximately 0.48% to 0.64%, indicating low sugar content and a mildly acidic to neutral taste profile (Pandey et al., 2021).

Starch content in *C. callosus* fruits varies between 1.17% and 3.50%, with higher values generally observed in immature fruits (Dahot et al., 1999). As fruits mature, starch is partially hydrolyzed into soluble sugars, contributing to reduced bitterness and improved palatability(Dirpan et al., 2021; Vidal et al., 2025). The low glycaemic load associated with these carbohydrate profiles supports the suitability of *C. callosus* for diabetic and low-sugar diets (Verma et al., 2015; Deepika et al., 2023).

5.3 Mineral composition

Cucumis callosus fruits are a valuable source of essential minerals, particularly iron and zinc, which are often deficient in diets of arid and semi-arid regions. Iron content ranges from approximately 0.21 to 4.06 mg per 100 g fresh weight, while zinc content ranges from 0.015 to 1.498 mg per 100 g (Dahot et al., 1999; Pandey et al., 2021). The relatively high mineral content of choti kachri compared to other kachri types has been attributed to both genetic factors and soil mineral availability in arid regions (Boora et al., 2025). Adequate intake of iron and zinc is critical for preventing anemia, supporting immune function, and maintaining metabolic health, highlighting the nutritional relevance of *C. callosus* in vulnerable populations.

5.4 Vitamins and antioxidant micronutrients

Cucumis callosus contains appreciable levels of vitamin C (ascorbic acid), with reported values ranging from approximately 6.57 to 25.9 mg per 100 g fresh weight (Chaturvedi & Nagar, 2001; Deepika et al., 2023). Ripe fruits of *Cucumis callosus* are consumed as a dessert fruit, whereas immature fruits are commonly used as vegetables. The fruits are also recognized as a source of vitamin C (Singh & Joshi, 2010). Vitamin C contributes significantly to the antioxidant capacity of the fruit and plays essential roles in immune function, collagen synthesis, and protection against oxidative stress(Kükürt & Gelen, 2024; Linster & Schaftingen, 2006).

In addition to vitamin C, *C. callosus* fruits and seeds contain carotenoids, including β-carotene, which serves as a precursor of vitamin A and contributes to antioxidant activity (Chaturvedi & Nagar, 2001; Chand et al., 2012). Tocopherols (vitamin E) are predominantly localized in the seeds and seed oil, where they contribute to lipid stability and cardioprotective effects (Mariod & Matthaus, 2008; Gupta et al., 2021).

5.5 Seed nutritional composition and oil quality

Seeds of *C. callosus* represent a nutritionally dense component of the plant and are often underutilized or discarded during processing. Seed oil content is relatively high, and the oil is rich in unsaturated fatty acids, particularly linoleic and α-linolenic acids, which are associated with improved lipid metabolism and cardiovascular health (Mariod & Matthaus, 2008).

The presence of natural antioxidants such as tocopherols and phytosterols enhances the oxidative stability of the seed oil, making it suitable for potential food and nutraceutical applications (Rangkadilok et al., 2010). Comparative studies with other *Cucumis* species indicate that the fatty acid profile of *C. callosus* seed oil is comparable to commonly consumed vegetable oils, further supporting its industrial relevance.

5.6 Nutritional variability and influencing factors

Considerable variability exists in the nutritional composition of *C. callosus* fruits and seeds, influenced by genetic diversity, environmental conditions, soil fertility, maturity stage, and post-harvest handling practices (Pandey et al., 2021; Boora et al., 2025). Wild and semi-domesticated populations often exhibit higher mineral and phytochemical contents than cultivated or managed populations, reflecting adaptive responses to environmental stress(Vaghasiya & Ishnava, 2024).

Seasonal variation also plays a significant role, with fruits harvested during optimal post-monsoon periods generally exhibiting higher nutritional quality(Boora et al., 2025). Such variability underscores the importance of standardized cultivation, harvesting, and processing protocols for maximizing nutritional benefits and ensuring consistent quality in value-added products.

5.7 Nutritional relevance and public health implications

The nutritional profile of *Cucumis callosus*—characterized by moderate protein, high dietary fiber, essential minerals, antioxidant vitamins, and low fat and sugar content—aligns well with dietary recommendations for the prevention and management of non-communicable diseases, including diabetes, cardiovascular disorders, and obesity (Ayomoh, 2021; Jailobaeva et al., 2021).

In arid and resource-poor regions, incorporation of *C. callosus* into local food systems can contribute to dietary diversification, micronutrient security, and resilience against climate-induced food shortages. Available research indicates that the fruits of *Cucumis callosus* provide adequate levels of essential nutrients, highlighting their potential as a valuable source of nutrition for human consumption (Ediriweera & Ratnasooriya, 2009). Its potential integration into functional foods, nutraceuticals, and health-oriented dietary formulations further expands its relevance beyond traditional consumption contexts (Deepika et al., 2023).

6. Phytochemical Profile and Bioactive Constituents of *C. callosus*

6.1 Overview of phytochemical diversity

Cucumis callosus is a rich reservoir of diverse phytochemicals that contribute to its sensory attributes, nutritional quality, and therapeutic potential. Phytochemical investigations conducted on different plant parts—including fruits, seeds, leaves, and roots—have revealed the presence of flavonoids, phenolic acids, tannins, alkaloids, carotenoids, saponins, terpenoids, sterols, and triterpenoid compounds (Chand et al., 2012; Deepika et al., 2023; Deepika et al., 2024).

The phytochemical composition of *C. callosus* varies with plant part, developmental stage, genotype, environmental conditions, and extraction solvent, reflecting the species' high metabolic plasticity and adaptive responses to abiotic stress. Such chemical diversity underpins both its ecological fitness and wide-ranging biological activities. The major classes of phytochemicals identified in Cucumis callosus, their predominant plant parts, and associated functional relevance are summarized in Table 4.

Phytochemical class	Plant part	Functional relevance
Cucurbitacins	Fruit, seed	Anticancer, anti-inflammatory
Phenolic compounds	Fruit pulp	Antioxidant
Flavonoids	Fruit, leaves	Antidiabetic, cardioprotective
Alkaloids	Fruit	Antimicrobial
Tannins	Seed coat	Antioxidant, astringent
Carotenoids	Fruit	Provitamin A, antioxidant
Omega-3 fatty acids	Seeds	Cardioprotective

Table 4. Major phytochemicals identified in *Cucumis callosus.* Source: Deepika et al., (2023); Sebastian et al. (2010)

6.2 Cucurbitacins: occurrence and biological significance

Cucurbitacins are highly oxygenated tetracyclic triterpenoids characteristic of the Cucurbitaceae and represent the most prominent bioactive constituents of *C. callosus*. Among these, cucurbitacin B is the predominant compound identified in fruit pericarp and pulp, particularly in immature fruits (Chand et al., 2012; Deepika et al., 2023).

Cucurbitacin B is responsible for the characteristic bitterness of immature kachri fruits(Metcalf et al., 1980; Olarewaju et al., 2021) and functions as a chemical defense mechanism against herbivores and pathogens(Bruno et al., 2022). Its concentration decreases as fruits mature, coinciding with reduced bitterness and improved palatability for human consumption (Deepika et al., 2023). Biosynthetically, cucurbitacins derive from the mevalonate pathway(Hua et al., 2019), and their accumulation is influenced by genetic and environmental factors, including drought and temperature stress(Mkhize et al., 2021; Zhao et al., 2022).

6.3 Phenolic acids and flavonoids

Phenolic compounds constitute a major class of secondary metabolites in *C. callosus*. Quantitative and qualitative analyses have identified various phenolic acids and flavonoids in *C. callosus*(Chaudhary & Gupta, 2025; Vaghasiya & Ishnava, 2024). These compounds contribute significantly to antioxidant capacity through mechanisms such as free-radical scavenging, metal ion chelation, and modulation of endogenous antioxidant enzymes(Lima et al., 2006; Soobrattee et al., 2005). The distribution of phenolics varies across plant parts, with higher concentrations generally reported in seeds and fruit peels compared to pulp tissues (Chand et al., 2012).

6.4 Carotenoids, vitamins, and lipophilic bioactives

Carotenoids, particularly β-carotene, have been detected in *C. callosus* fruits and contribute to both nutritional value and antioxidant activity (Chaturvedi & Nagar, 2001). These compounds serve as precursors of vitamin A and play important roles in vision, immune function, and cellular differentiation(Álvarez et al., 2013). Seed oil contains appreciable amounts of tocopherols, phytosterols, and other lipophilic antioxidants that enhance oxidative stability and confer cardioprotective properties (Mariod & Matthaus, 2008; Rangkadilok et al., 2010). The presence of these compounds supports the potential use of *C. callosus* seed oil in functional foods and nutraceutical formulations.

6.5 Alkaloids, tannins, saponins, and other secondary metabolites

Qualitative phytochemical screening revealed the presence of alkaloids, tannins, saponins, and glycosides in various extracts of *C. callosus* (Chand et al., 2012). Tannins contribute to astringency and antimicrobial activity(Dogbey et al., 2020; Huang et al., 2024), while saponins are associated with cholesterol-lowering, immunomodulatory, and anti-inflammatory effects(Francis et al., 2002; Kręgiel et al., 2017). Although present in relatively lower concentrations compared to phenolics and cucurbitacins, these compounds may act synergistically to enhance the overall bioactivity of *C. callosus* extracts. The complexity of this phytochemical matrix underscores the importance of whole-plant and whole-food approaches when evaluating biological effects.

6.6 Analytical techniques for phytochemical characterization

A range of analytical techniques has been employed to characterize the phytochemical constituents of *C. callosus*. Preliminary qualitative screening is typically conducted using standard colorimetric assays, while quantitative estimation of total phenolics and flavonoids is performed using Folin–Ciocalteu and aluminum chloride methods, respectively (Chand et al., 2012).

Advanced chromatographic and spectroscopic techniques, including high-performance liquid chromatography (HPLC), gas chromatography–mass spectrometry (GC–MS), liquid chromatography–mass spectrometry (LC–MS), and nuclear magnetic resonance (NMR) spectroscopy, have been used to identify and quantify individual bioactive compounds (Yasir et al., 2016; Deepika et al., 2024). These approaches provide high-resolution insights into the phytochemical complexity of the species and enable correlation of specific compounds with biological activities.

6.7 Influence of environmental and post-harvest factors

Phytochemical accumulation in *C. callosus* is strongly influenced by environmental conditions such as temperature, water availability, soil fertility, and light intensity. Plants grown under stress conditions often exhibit elevated levels of phenolics and cucurbitacins, reflecting adaptive metabolic responses to environmental challenges (Pandey et al., 2021).

Post-harvest handling, drying, and processing methods also affect phytochemical retention(Jia et al., 2025). Traditional sun drying may lead to partial degradation of heat- and light-sensitive compounds, whereas controlled drying and irradiation techniques have been shown to improve retention of bioactive constituents (Chaturvedi & Nagar, 2001; Nathawat et al., 2013; Deepika et al., 2024).

6.8 Phytochemical relevance to functional and therapeutic applications

The diverse phytochemical profile of *Cucumis callosus* provides a strong biochemical basis for its reported antioxidant, antidiabetic, anti-inflammatory, antihyperlipidemic, antimicrobial, and anticancer activities. The bioactive compounds contribute to its demonstrated anti-inflammatory, anticancer, hypoglycemic, antioxidant, and anti-adipogenic effects within the human body. Numerous studies have reported the presence of flavonoids, tannins, total alkaloids, and phenolic compounds in *Cucumis callosus*, which are primarily responsible for its therapeutic potential (Haldhar et al., 2018). Synergistic interactions among cucurbitacins, phenolics, flavonoids, carotenoids, and vitamins likely contribute to the broad spectrum of biological effects observed in experimental studies (Akbari et al., 2022; Deepika et al., 2023).

Understanding the phytochemical composition and variability of *C. callosus* is therefore essential for optimizing its use in functional foods, nutraceuticals, and plant-based therapeutic formulations, as well as for guiding future breeding and processing strategies aimed at enhancing bioactive compound content.

7. Pharmacological and Therapeutic Properties of *Cucumis callosus*

7.1 Antioxidant activity

Oxidative stress, resulting from an imbalance between reactive oxygen species (ROS) production and antioxidant defense mechanisms, is implicated in the pathogenesis of numerous chronic diseases, including diabetes, cardiovascular disorders, neurodegenerative diseases, and cancer (Akbari et al., 2022; Wendt et al., 2023). Plant-derived antioxidants play a crucial role in neutralizing free radicals and mitigating oxidative damage at cellular and molecular levels(Kasote et al., 2015).

Extracts prepared from fruits and seeds of *Cucumis callosus* have demonstrated significant antioxidant activity in various in vitro assays, including DPPH, ABTS, FRAP, and reducing power assays (Chand et al., 2012). The aqueous and alcoholic extracts of *Cucumis callosus* seeds have been reported to exhibit significant antioxidant activity (Trivedi, 2006). Methanolic and alcoholic seed extracts exhibited free-radical scavenging activity, showing a moderate positive correlation between DPPH radical scavenging capacity and total phenolic content, and a strong one with total flavonoid content for the Cucurbitaceae family, suggesting these compounds contribute to antioxidant potential(Akhter et al., 2022).

The presence of phenolic acids, flavonoids, carotenoids, vitamin C, and tocopherols enhances the overall antioxidant capacity of *C. callosus* and supports its traditional use in mitigating heat stress and inflammatory conditions (Chaturvedi & Nagar, 2001; Deepika et al., 2023). These findings suggest that regular dietary intake of *C. callosus* may contribute to improved redox balance and protection against oxidative stress-related disorders.

7.2 Antidiabetic activity and glycemic regulation

Diabetes mellitus is a major non-communicable disease characterized by chronic hyperglycemia and associated metabolic complications. Oxidative stress, impaired insulin signaling, and pancreatic β-cell dysfunction are central to diabetes pathophysiology (Østergaard et al., 2020).

Several experimental studies have demonstrated the antidiabetic potential of *Cucumis callosus*. In vivo studies using alloxan- and streptozotocin-induced diabetic rat models showed that administration of aqueous, ethanolic, and methanolic extracts of *C. callosus* fruits and seeds resulted in significant reductions in fasting blood glucose levels, comparable to standard antidiabetic drugs such as glibenclamide and metformin (Verma et al., 2015).

The hypoglycemic effects of *C. callosus* have been attributed to multiple mechanisms, including inhibition of carbohydrate-digesting enzymes such as α-amylase and α-glucosidase, enhancement of peripheral glucose uptake, protection of pancreatic β-cells from oxidative damage, and modulation of insulin signaling pathways (Deepika et al., 2023). The high dietary fiber content of the fruit may further contribute to improved glycemic control by slowing glucose absorption in the gastrointestinal tract.

7.3 Antihyperlipidemic and cardioprotective effects

Dyslipidemia is a key risk factor for cardiovascular diseases, which remain the leading cause of mortality worldwide. Plant-based diets rich in antioxidants, dietary fiber, and unsaturated fatty acids have been shown to improve lipid profiles and reduce cardiovascular risk (Chen & Zhang, 2021).

Administration of *Cucumis callosus* extracts in experimental animal models has resulted in significant reductions in serum total cholesterol, triglycerides, and low-density lipoprotein (LDL) cholesterol, along with concomitant increases in high-density lipoprotein (HDL) cholesterol levels (Varadharajan et al., 2016). These lipid-modulating effects are attributed to the presence of flavonoids, phenolic compounds, and omega-3 fatty acids, which influence lipid metabolism, inhibit lipid peroxidation, and improve endothelial function(DEEPIKA et al., 2023; Sahu et al., 2026).

Seed oil of *C. callosus*, rich in unsaturated fatty acids and tocopherols, further supports its cardioprotective potential by enhancing antioxidant defense and reducing oxidative modification of lipoproteins (Mariod & Matthaus, 2008; Rangkadilok et al., 2010). Collectively, these findings highlight the potential role of *C. callosus* in dietary strategies aimed at cardiovascular health promotion.

7.4 Anti-inflammatory activity

Chronic inflammation is closely linked to the development and progression of metabolic disorders, cardiovascular diseases, and cancer(Furman et al., 2019). Bioactive phytochemicals capable of modulating inflammatory pathways are therefore of considerable therapeutic interest.

Phytochemicals present in *C. callosus*, particularly flavonoids and phenolic acids, have been shown to exhibit anti-inflammatory activity through inhibition of pro-inflammatory mediators, reduction of ROS generation, and modulation of signaling pathways such as NF-κB and MAPK (Akbari et al., 2022; Deepika et al., 2023). Although detailed mechanistic studies specific to *C. callosus* remain limited, existing evidence supports its traditional use in managing inflammatory conditions.

7.5 Anticancer potential

Cancer remains a leading cause of morbidity and mortality worldwide, necessitating the exploration of novel chemopreventive and therapeutic agents derived from natural sources(Deng et al., 2024). Cucurbitacins, particularly cucurbitacin B, have attracted attention due to their potent anticancer properties(Garg et al., 2017). A notable bioactive compound isolated from the pericarp of kachri is cucurbitacin B, a triterpenoid known to exhibit strong antiproliferative activity against cancer cells (Rolim et al., 2020).

Cucurbitacin B isolated from *C. callosus* pericarp has demonstrated antiproliferative and pro-apoptotic activity against various cancer cell lines, including Ehrlich ascites carcinoma and breast cancer models (Panda et al., 2018). These effects are mediated through modulation of key signaling pathways such as JAK–STAT, PI3K–Akt, and MAPK, leading to cell cycle arrest, apoptosis induction, and inhibition of tumor growth(Garg et al., 2017).

The anticancer potential of *C. callosus* is further supported by the presence of flavonoids and phenolic compounds, which contribute to chemopreventive effects through antioxidant and anti-inflammatory mechanisms (Deepika et al., 2023).

7.6 Antimicrobial and other therapeutic activities

Extracts of *Cucumis callosus* have shown antimicrobial activity against a range of bacterial and fungal pathogens, supporting its traditional use in treating infections and skin disorders (Chand et al., 2012). The antimicrobial effects are attributed to the combined action of phenolics, flavonoids, and saponins, which disrupt microbial cell membranes and inhibit enzymatic activity(Boora et al., 2025).

Additional therapeutic properties reported for *C. callosus* include hepatoprotective, gastroprotective, and immunomodulatory effects, although these areas remain underexplored and warrant further systematic investigation (Deepika et al., 2023). A consolidated overview of the major pharmacological and therapeutic activities of Cucumis callosus, along with the corresponding experimental or traditional evidence, is presented in Table 5.

Activity	Evidence reported
Antioxidant	High phenolic and flavonoid content
Antidiabetic	Enzyme inhibition and glucose regulation
Antihyperlipidaemic	Lipid-lowering effects
Antimicrobial	Activity against bacterial strains
Anti-inflammatory	Traditional and experimental support
Anticancer	Cucurbitacin-mediated cytotoxicity
Meat tenderization	Proteolytic enzyme activity

Table 5. Pharmacological and therapeutic activities of *Cucumis callosus.* Source: Deepika et al., (2023); Panda & Haldar (2016).

7.7 Safety considerations and toxicological aspects

Despite extensive traditional consumption, comprehensive toxicological evaluations of *Cucumis callosus* are limited. Cucurbitacins, while pharmacologically potent, are known to exhibit dose-dependent toxicity at high concentrations, leading to gastrointestinal irritation and systemic adverse effects (Deepika et al., 2023). Therefore, controlled dose–response studies, long-term toxicity assessments, and clinical trials are essential to establish safe intake levels and ensure consumer safety, particularly for concentrated extracts and nutraceutical formulations.

8. Ethnobotanical and Traditional Uses of *Cucumis callosus*

Cucumis callosus holds a prominent place in the traditional food systems and ethnomedicinal practices of arid and semi-arid regions of India. The species has been used historically by indigenous and rural communities for culinary, medicinal, and socio-cultural purposes, reflecting deep-rooted traditional knowledge systems adapted to harsh environmental conditions(Panda et al., 2016; Vaghasiya & Ishnava, 2024).

Ethnobotanical surveys conducted across Rajasthan, Gujarat, Haryana, Odisha, Maharashtra, and parts of southern India document extensive use of various plant parts of *C. callosus*, including fruits, seeds, flowers, leaves, and roots (Meena et al., 2016; Gadekar, 2023; Deepika et al., 2023). These uses are closely linked to seasonal availability, climatic conditions, and local dietary habits.

8.1 Traditional culinary uses

The immature and mature fruits of *Cucumis callosus* are widely consumed as vegetables in fresh and dried forms. It is an ideal summer vegetable crop, primarily cultivated for its edible tender fruits, which are preferred as salad components, pickles, dessert fruits, and cooked vegetables in traditional food systems (Haldhar et al., 2017). Figure 3 illustrates freshly harvested fruits of Cucumis callosus and a traditional pulp preparation commonly used in indigenous culinary and ethnomedicinal practices. Fresh fruits are cooked as curries or vegetables, often combined with pulses or cereals, while dried fruits constitute a key ingredient in traditional dishes of arid regions(Choudhary et al., 2023; Panda et al., 2016). One of the most notable culinary preparations is *Panchkuta*, a traditional Rajasthani dish prepared using dried kachri along with other desert-adapted species such as *Capparis decidua* (ker), *Prosopis cineraria* (sangri), *Cordia dichotoma* (gunda), and *Citrullus colocynthis* (kumti) (Meena et al., 2016; Boora et al., 2015).

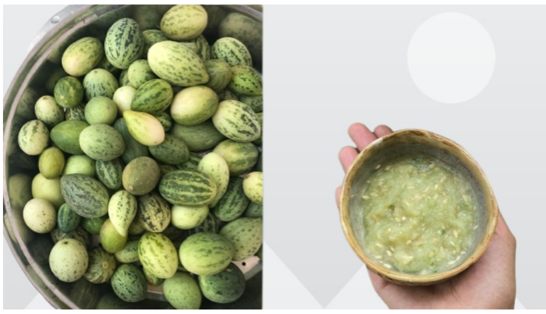

Figure 3. Fresh fruits of *Cucumis callosus* (left) and traditional pulp preparation (right) used in household-level culinary and ethnobotanical practices.

Dried kachri slices or powder is also used as a souring agent in vegetable preparations, chutneys, spice blends, and pickles(Alshammari et al., 2026; Choudhary et al., 2023). In several regions, powdered kachri is added to buttermilk-based preparations and savory snacks to enhance flavor and shelf life(Alshammari et al., 2026; Boora et al., 2025).

A unique and culturally significant application of *C. callosus* is its use as a natural meat tenderizer. Traditional households use dried or powdered kachri to tenderize tough cuts of meat, particularly in mutton and game meat preparations(Gagaoua et al., 2023; Maheswarappa et al., 2004). This practice is attributed to the presence of proteolytic enzymes that break down muscle proteins, improving texture and palatability(Azmi et al., 2023; Maheswarappa et al., 2004).

8.2 Ethnomedicinal uses

Beyond its culinary importance, *Cucumis callosus* is widely valued for its medicinal properties in traditional healthcare systems. Various parts of the plant are used either alone or in combination with other medicinal plants to treat a wide range of ailments(El-Sayed et al., 2026; Sahu et al., 2026). In eastern India, particularly among tribal communities of Balasore and Baripada districts of Odisha, the fruits of *Cucumis callosus* are traditionally used during religious worship and are also employed in folk medicine for the management of diabetes, epilepsy, and diarrhea (Harborne, 1998).

Traditional healers and local communities use fruit pulp and juice to manage digestive disorders, constipation, indigestion, and stomach discomfort(Panda et al., 2016; Sahu et al., 2026). The fruits are also consumed during summer months to alleviate heat stress, dehydration, and fatigue, owing to their high moisture content and cooling properties (Gadekar, 2023). In traditional practice, a tablespoon of *Cucumis callosus* seeds mixed with water is consumed to mitigate the effects of heat waves in arid and hot regions (Kumar et al., 2008).

Seeds of *C. callosus* are traditionally used for managing urinary disorders, kidney-related ailments, and metabolic conditions such as diabetes. Seed paste or decoctions are administered orally, while seed oil is sometimes applied externally for skin conditions(Boora et al., 2025; Sahu et al., 2026).

Leaves and roots are used in poultices and topical applications to treat skin infections, inflammation, wounds, and insect bites. The flake extract of *Cucumis callosus* has been applied topically in traditional medicine to heal skin cracks (Ali et al., 2006). Consistent topical application of dehydrated kachri powder has been traditionally reported to alleviate minor skin ailments, including bedsores, rashes, lice infestations, boils, earaches, itching, and prickly heat (Nandal & Bhardwaj, 2015). In some tribal communities, root extracts are administered as an anthelmintic and for alleviating joint pain and swelling (Gadekar, 2023).

8.3 Traditional preservation practices

Traditional knowledge systems include several preservation methods to extend the availability of *C. callosus* beyond its short harvesting season. Sun drying of sliced fruits is a common method, practiced in Rajasthan and Gujarat(DEEPIKA et al., 2023; Patel & Panwar, 2022). Dried fruits are stored for year-round use, particularly during drought periods when fresh vegetables are scarce (Meena et al., 2016).

Drying is often carried out in open sunlight, sometimes preceded by blanching(Ramyashree et al., 2024). Although effective, these traditional methods may result in partial nutrient loss, highlighting the need for improved yet culturally acceptable preservation technologies (Chaturvedi & Nagar, 2001; Nathawat et al., 2013).

8.4 Cultural and socio-economic significance

Cucumis callosus plays an important role in the socio-cultural fabric of arid-zone communities. Its collection, drying, storage, and use are often integrated into household food security strategies and seasonal livelihood activities, particularly for women (Meena et al., 2016).

Local markets in arid regions frequently trade dried kachri, providing supplemental income to rural households(Boora et al., 2025; DEEPIKA et al., 2023). The species thus contributes not only to nutrition and health but also to socio-economic resilience in marginal environments (Gadekar, 2023; Boora et al., 2025).

8.5 Convergence of traditional knowledge and modern science

There is a strong convergence between traditional uses of *Cucumis callosus* and findings from modern phytochemical and pharmacological studies. Traditional claims related to digestive health, metabolic regulation, anti-inflammatory effects, and heat stress mitigation are increasingly supported by experimental evidence demonstrating antioxidant, antidiabetic, antimicrobial, and anti-inflammatory activities (Deepika et al., 2023).

Such convergence underscores the scientific validity of indigenous knowledge systems and highlights the importance of integrating ethnobotanical insights with modern research to guide functional food development, nutraceutical formulation, and sustainable commercialization of *C. callosus*.

9. Post-Harvest Losses and Preservation of *Cucumis callosus*

Fruits and vegetables are important sources of essential health-promoting nutrients such as vitamins, minerals, and dietary fiber(Slavin & Lloyd, 2012). However, owing to their high moisture content—often exceeding 80%—fresh fruits and vegetables are classified as highly perishable commodities (Changrue et al., 2006). Post-harvest losses represent a major constraint in the utilization and commercialization of *Cucumis callosus*, particularly due to its high moisture content, tender tissue structure, and seasonal availability. The kachri fruit has a limited availability period, and because of its short shelf life, it generally becomes unsuitable for human consumption within a week after harvest(Patel & Panwar, 2022). As a result, only a small proportion of the total kachri yield is utilized profitably during its brief harvesting season (Patel & Panwar, 2022). Like many cucurbitaceous vegetables, *C. callosus* fruits are highly perishable and susceptible to rapid physiological deterioration and microbial spoilage if not processed or preserved promptly after harvest (Nathawat et al., 2013; Deepika et al., 2023).

Field-based assessments and traditional knowledge indicate that post-harvest losses of fresh *C. callosus* fruits may range from 30–40%, especially under ambient storage conditions prevalent in arid and semi-arid regions. High temperatures, low relative humidity, mechanical damage during harvesting and transport, and lack of cold-chain infrastructure further exacerbate these losses (Gadekar, 2023; Boora et al., 2025).

9.1 Physiological and microbial causes of post-harvest losses

The high moisture content (80–97%) and soft pericarp of *C. callosus* fruits promote rapid respiration and transpiration, leading to weight loss, textural degradation, and shriveling during storage (Pandey et al., 2021). Elevated respiration rates accelerate senescence, reducing marketable shelf life(Lufu et al., 2020).

Microbial spoilage is another major contributor to post-harvest losses. Fresh fruits are vulnerable to contamination by bacteria, yeasts, and molds, particularly when harvested during humid post-monsoon periods. Common spoilage organisms include *Aspergillus*, *Penicillium*, and *Rhizopus* species, which cause soft rot and surface decay under favorable conditions (Nathawat et al., 2013).

9.2 Traditional post-harvest handling practices

Traditional post-harvest handling for *C. callosus* primarily involves sun drying, which is widely practiced in Rajasthan, Gujarat, and other arid regions; fruits are sliced longitudinally or transversely and dried under open sunlight for several days until moisture content is sufficiently reduced to inhibit microbial growth (Meena et al., 2016).

In some regions, fruits are lightly salted or blanched prior to drying to reduce bitterness and microbial load. Dried kachri is then stored in airtight containers or cloth bags and used throughout the year as a vegetable, condiment, or spice ingredient. Figure 4 shows dried roots of *Cucumis callosus*, which represent the most common traditional post-harvest preservation form used in arid and semi-arid regions. While these methods are effective in extending shelf life, they often result in partial losses of heat- and light-sensitive nutrients such as vitamin C and carotenoids (Chaturvedi & Nagar, 2001).

Figure 4. Traditionally sun-dried roots of *Cucumis callosus* used for long-term storage and household-level food preparation.

9.3 Modern preservation approaches

To address the limitations of traditional methods, modern preservation techniques have been explored to improve shelf life, safety, and nutritional retention of *C. callosus*.

9.3.1 Gamma irradiation

Gamma irradiation has emerged as an effective non-thermal preservation method for *C. callosus*. Nathawat et al. (2013) demonstrated that gamma irradiation at a dose of 5 kGy significantly reduced microbial load in dried kachri without adversely affecting its nutritional composition, sensory quality, or phytochemical content. Irradiated samples exhibited improved microbial safety and extended storage stability compared to non-irradiated controls.

Gamma irradiation is particularly advantageous because it does not involve high temperatures, thereby preserving heat-sensitive bioactive compounds and maintaining product quality. Its application holds promise for large-scale preservation and commercialization of dried kachri products.

9.3.2 Controlled drying techniques

Improved drying methods such as solar drying, hot-air drying, and low-temperature dehydration have been shown to enhance drying efficiency and nutrient retention compared to traditional sun drying. Controlled drying reduces exposure to excessive heat, ultraviolet radiation, and environmental contaminants, thereby preserving vitamins, phenolic compounds, and sensory attributes (Chaturvedi & Nagar, 2001; Deepika et al., 2024).

9.4 Storage stability and shelf-life extension

Proper packaging and storage conditions are critical for maintaining the quality of dried *C. callosus*. The use of moisture-proof packaging materials, such as laminated pouches or airtight containers, helps prevent moisture reabsorption and microbial growth. Storage in cool, dry environments further enhances shelf life and prevents quality deterioration (Nathawat et al., 2013).

Studies indicate that dried kachri preserved using improved drying and irradiation techniques can be stored safely for several months without significant losses in nutritional or sensory quality, making it suitable for year-round consumption and commercial distribution(Nathawat et al., 2011).

9.5 Implications for food security and commercialization

Reducing post-harvest losses through improved preservation strategies is essential for enhancing the utilization, marketability, and economic value of *Cucumis callosus*. Effective post-harvest management can increase availability during off-season periods, support value addition, and improve income opportunities for rural communities in arid regions (Boora et al., 2025).

Integration of traditional knowledge with scientifically validated preservation technologies offers a sustainable pathway for minimizing losses while retaining cultural acceptability and nutritional benefits. Such approaches are critical for mainstreaming *C. callosus* into formal food systems and functional food value chains.

10. Drying, Dehydration, and Irradiation Technologies for *Cucumis callosus*

Drying and dehydration are the most widely practiced preservation techniques for *Cucumis callosus*, owing to the fruit's high moisture content, seasonal availability, and traditional consumption patterns in arid regions. These technologies play a critical role in extending shelf life, reducing post-harvest losses, and enabling year-round utilization of kachri in household and commercial food systems (Chaturvedi & Nagar, 2001; Nathawat et al., 2013; Deepika et al., 2023).

10.1 Traditional sun drying

Sun drying is the oldest and most commonly employed method for preserving *C. callosus* fruits. In traditional practice, freshly harvested fruits are washed, sliced longitudinally or into rings, and spread on clean surfaces or mats under direct sunlight for several days until adequate moisture reduction is achieved (Meena et al., 2016; Gadekar, 2023).

Sun drying is favored for its simplicity, low cost, and cultural acceptability. However, prolonged exposure to high temperatures, ultraviolet radiation, dust, insects, and fluctuating environmental conditions can lead to uneven drying, microbial contamination, and degradation of heat- and light-sensitive nutrients such as vitamin C, carotenoids, and certain phenolic compounds (Chaturvedi & Nagar, 2001). Despite these limitations, sun drying remains an integral component of traditional food preservation systems in arid and semi-arid regions.

10.2 Improved solar drying systems

To overcome the drawbacks of open sun drying, improved solar drying systems have been introduced in some regions. Solar dryers provide controlled airflow, higher drying efficiency, and protection from environmental contaminants. Use of indirect or mixed-mode solar dryers has been shown to reduce drying time while improving retention of nutritional and phytochemical constituents in dried kachri products (Chaturvedi & Nagar, 2001; Deepika et al., 2024).

Solar drying also offers advantages in terms of energy efficiency and sustainability, making it particularly suitable for rural and off-grid communities(There & Sharma, 2024; Udomkun et al., 2020). Adoption of such technologies can significantly enhance product quality while maintaining affordability and cultural relevance.

10.3 Hot-air drying and low-temperature dehydration

Hot-air drying involves passing heated air over sliced fruits at controlled temperatures, typically ranging from 40 to 60 °C. This method enables uniform drying, reduced microbial load, and improved product consistency compared to traditional sun drying(Manzoor et al., 2019). Studies indicate that low-temperature hot-air drying helps preserve phenolic compounds, color, and textural properties of *C. callosus* fruits more effectively than high-temperature drying (Chaturvedi & Nagar, 2001).

Low-temperature dehydration minimizes thermal degradation of vitamins and bioactive compounds and is therefore suitable for producing high-quality dried kachri powders intended for functional food and nutraceutical applications(Ramachandran et al., 2024). However, higher operational costs and energy requirements may limit widespread adoption in resource-poor settings(Ciurzyńska & Lenart, 2011).

10.4 Pretreatments to enhance drying efficiency

Pretreatments such as blanching, salting, and osmotic dehydration are sometimes employed prior to drying to improve drying efficiency, reduce bitterness, and enhance microbial safety(Mu et al., 2024). Blanching can inactivate enzymes responsible for oxidative browning and quality deterioration, while salting may reduce water activity and inhibit microbial growth (Nathawat et al., 2013).

However, excessive blanching or salting may lead to nutrient leaching and loss of water-soluble vitamins(Mehlomakulu & Emmambux, 2020). Therefore, optimization of pretreatment conditions is essential to balance quality retention with preservation efficacy.

10.5 Gamma irradiation as a complementary technology

Gamma irradiation has been explored as a complementary preservation technology for dried *C. callosus*. Irradiation at doses up to 5 kGy has been shown to significantly reduce microbial load, including pathogenic bacteria and spoilage fungi, without adversely affecting sensory quality, nutritional composition, or phytochemical content (Nathawat et al., 2013).

Unlike thermal treatments, gamma irradiation does not raise product temperature, making it particularly effective for preserving heat-sensitive bioactive compounds(Colletti et al., 2024). When combined with drying, irradiation can substantially enhance shelf life and safety of kachri products, supporting their commercialization and export potential(Colletti et al., 2024; Nathawat et al., 2011).

10.6 Impact of processing on nutritional and phytochemical quality

Processing methods have a significant influence on the nutritional and phytochemical profile of *Cucumis callosus*. Traditional sun drying may result in partial losses of vitamin C, carotenoids, and phenolics due to prolonged exposure to heat and light(Grosshagauer et al., 2021; Skåra et al., 2022). In contrast, controlled drying and irradiation techniques generally offer improved retention of these compounds (Chaturvedi & Nagar, 2001; Deepika et al., 2024).

Retention of antioxidant activity and bioactive compounds is a key consideration for the development of functional foods and nutraceutical products. Therefore, selection and optimization of drying and preservation technologies should be guided by both nutritional quality and economic feasibility.

10.7 Relevance to value addition and commercialization

Drying, dehydration, and irradiation technologies are central to the value addition of *Cucumis callosus*. Dried fruits and powders serve as raw materials for spice blends, functional ingredients, nutraceutical formulations, and traditional foods. Improved processing techniques enhance product safety, consistency, and marketability, enabling integration of kachri into formal food value chains (Deepika et al., 2023).

The adoption of appropriate preservation technologies, combined with standardized processing protocols and quality control measures, is essential for scaling up production and ensuring consumer confidence in *C. callosus*-based products.

11. Processing and Value Addition of *Cucumis callosus*

Processing and value addition of *Cucumis callosus* play a pivotal role in enhancing its utilization, shelf life, marketability, and economic value, particularly in arid and semi-arid regions where the crop is traditionally grown. Given its seasonal availability and high perishability, processing transforms *C. callosus* from a subsistence food into a diversified raw material suitable for culinary, industrial, and nutraceutical applications (Deepika et al., 2023; Boora et al., 2025).

11.1 Traditional processing practices

Traditional processing of *C. callosus* is deeply embedded in local food cultures. Fresh fruits are commonly sliced and sun-dried to produce dried kachri, which is stored and consumed throughout the year. Dried fruits are rehydrated and cooked as vegetables, added to curries, or used as souring agents in traditional recipes (Meena et al., 2016).

Powdered dried kachri is widely used in spice blends and chutneys, imparting characteristic flavor and mild acidity. In some regions, dried fruits are roasted and ground to produce seasoning powders used in savory snacks and buttermilk-based preparations (Gadekar, 2023). Figure 5 illustrates fresh fruits of Cucumis callosus and their traditionally dried form, which represents the most common primary value-added product used in household and commercial preparations in arid regions. The diverse traditional and value-added forms of Cucumis callosus and their corresponding culinary, functional, and nutraceutical applications are summarized in Table 6.

Figure 5. Fresh fruits of *Cucumis callosus* (left) and traditionally dried kachri slices (right), commonly used for culinary applications, long-term storage, and value-added food preparations.

Product form	Application
Fresh fruit	Vegetable, salad
Dried slices/powder	Panchkuta, spice mixes
Paste/chutney	Traditional cuisine
Meat tenderizer	Proteolytic action
Functional ingredient	Nutraceutical formulations
Seed preparations	Cooling drink, oil source

Table 6. Traditional and value-added products from *Cucumis callosus*. Source: Bates et al. (1990); Pessarakli (2016).

11.2 Natural meat tenderizer and enzymatic applications

One of the most distinctive value-added uses of *Cucumis callosus* is its application as a natural meat tenderizer. Cucumin sourced from kachri has been reported to exhibit strong proteolytic activity, and coarsely ground dried kachri fruits are widely used as natural meat tenderizers in food preparation (Maiti et al., 2008). Traditional households use dried or powdered kachri to tenderize tough cuts of meat, particularly mutton and game meat. This practice is attributed to the presence of proteolytic enzymes capable of hydrolyzing muscle proteins, thereby improving meat tenderness and palatability(Gagaoua et al., 2020; Han et al., 2024). Cucumin extracted from kachri has been reported to possess strong proteolytic activity, and coarsely ground dried kachri fruits are traditionally used as natural meat tenderizers(Parkash et al., 2021). Comparative studies have demonstrated that *Cucumis callosus* enzymes can serve as a more effective alternative to papain for tenderizing tough buffalo meat (Naveena et al., 2004). Scientific investigations have confirmed the proteolytic activity of kachri extracts, highlighting their potential as natural alternatives to synthetic tenderizers and commercial enzymes(Maheswarappa et al., 2004; Parkash et al., 2021). Such applications are particularly relevant in clean-label food processing and traditional meat product formulations.

11.3 Development of dried products and powders

Dried *C. callosus* products, including slices, flakes, and powders, represent the most widely commercialized value-added forms. Improved drying technologies such as solar drying, hot-air drying, and low-temperature dehydration enhance product quality, color, and nutrient retention compared to traditional sun drying (Chaturvedi & Nagar, 2001; Deepika et al., 2024).

Powders produced from dried kachri are used as functional ingredients in soups, sauces, spice mixes, and ready-to-cook formulations(Bas-Bellver et al., 2022; Nathawat et al., 2011). Their low moisture content and extended shelf life make them suitable for storage, transportation, and incorporation into packaged food products(Patel & Panwar, 2022; Ueda et al., 2023).

11.4 Functional food and nutraceutical formulations

The rich nutritional and phytochemical profile of *C. callosus* has stimulated interest in its incorporation into functional foods and nutraceutical products. Dried fruit and seed powders are being explored for inclusion in dietary supplements, herbal formulations, and health-oriented food products aimed at managing metabolic disorders such as diabetes and hyperlipidaemia(DEEPIKA et al., 2023; Panda et al., 2018). Seed oil, rich in unsaturated fatty acids and tocopherols, offers potential for development of nutraceutical oils and functional lipid formulations(Ale et al., 2026; Han et al., 2024). The antioxidant and cardioprotective properties of these bioactives further enhance their market appeal (Mariod & Matthaus, 2008; Rangkadilok et al., 2010).

11.5 Industrial and commercial prospects

Beyond household-level processing, *C. callosus* offers opportunities for small-scale and industrial processing ventures. Standardization of drying, grinding, packaging, and quality control processes can facilitate commercialization of kachri-based products for regional and national markets(Hesham et al., 2020). Development of such value chains can generate employment, enhance rural incomes, and promote sustainable utilization of indigenous plant resources (Boora et al., 2025). Despite its potential, several challenges hinder large-scale processing and value addition of *C. callosus*. Integration of traditional knowledge with scientific innovation will be key to unlocking the full value of *C. callosus* in sustainable food systems.

12. Functional Food, Nutraceutical, and Industrial Potential of *Cucumis callosus*

The growing global emphasis on preventive healthcare, plant-based diets, and functional foods has renewed interest in underutilized crops with demonstrated nutritional and therapeutic benefits. In this context, *Cucumis callosus* emerges as a promising candidate for functional food and nutraceutical development due to its rich nutrient composition, diverse phytochemical profile, and validated pharmacological properties (Akbari et al., 2022; Deepika et al., 2023).

12.1 Functional food potential

Functional foods are defined as foods that provide health benefits beyond basic nutrition, contributing to disease risk reduction and improved physiological functions(Anwer & Ming, 2024; Mudondo et al., 2025). The nutritional profile of *C. callosus*, characterized by moderate protein content, high dietary fiber, essential minerals, antioxidant vitamins, and low fat and sugar content, aligns well with functional food criteria (Ayomoh, 2021; Jailobaeva et al., 2021).

Regular consumption of *C. callosus* in traditional diets has been associated with improved digestive health, glycemic regulation, and thermal comfort during hot seasons. Kachri has been reported to exert beneficial effects on digestive, cardiovascular, ocular, and skin health, while also contributing to enhanced energy levels (Vishwakarma et al., 2017). The presence of dietary fiber aids in gastrointestinal motility and glucose homeostasis, while antioxidants such as vitamin C, phenolics, and carotenoids contribute to oxidative stress reduction (Deepika et al., 2023).

Dried kachri products, powders, and extracts can be incorporated into functional food formulations such as soups, sauces, spice mixes, bakery products, and ready-to-cook foods(DEEPIKA et al., 2023; Patel & Panwar, 2022). Their compatibility with traditional culinary practices enhances consumer acceptance and facilitates mainstreaming into contemporary food systems.

12.2 Nutraceutical applications

Nutraceuticals derived from *C. callosus* hold significant promise for managing lifestyle-related disorders. Experimental studies demonstrating antidiabetic, antihyperlipidaemic, antioxidant, anti-inflammatory, and cardioprotective effects support its use in nutraceutical formulations aimed at metabolic health(DEEPIKA et al., 2023; Panda et al., 2018).

Seed oil rich in unsaturated fatty acids and tocopherols offers potential for development of nutraceutical oils and capsules targeted at cardiovascular health(Han et al., 2024; Jalili & Rashidi, 2024). Similarly, standardized extracts enriched with cucurbitacins, flavonoids, and phenolic compounds may be explored for formulation of herbal supplements, subject to safety and dosage validation (Deepika et al., 2023).

12.3 Industrial applications

Beyond food and nutraceutical uses, *Cucumis callosus* exhibits considerable industrial potential. The proteolytic enzymes present in kachri are already used traditionally as natural meat tenderizers and could be developed into commercial enzyme preparations for the food processing industry (Boora et al., 2025).

Seed oil and bioactive extracts may also find applications in cosmetic and pharmaceutical industries due to their antioxidant and anti-inflammatory properties(Ale et al., 2026; Fratianni et al., 2023). The development of such products aligns with the growing demand for natural, plant-derived ingredients in clean-label and sustainable product formulations.

12.4 Market prospects and value chain development

The commercialization of *C. callosus*-based functional foods and nutraceuticals requires the development of efficient value chains encompassing cultivation, post-harvest handling, processing, quality control, packaging, and marketing. Local and regional markets for dried kachri already exist in arid regions, indicating baseline consumer acceptance and demand (Gadekar, 2023).

Scaling up production and expanding market reach will depend on standardization of processing protocols, assurance of product safety and quality, and effective branding that highlights nutritional and functional benefits. Integration of farmer collectives, self-help groups, and small-scale enterprises can enhance economic viability and rural livelihoods.

12.5 Regulatory and safety considerations

For successful commercialization, functional foods and nutraceuticals derived from *C. callosus* must comply with regulatory standards governing food safety, labeling, and health claims. While traditional consumption suggests general safety, concentrated extracts and supplements require rigorous toxicological evaluation to establish safe intake levels (Deepika et al., 2023).

Cucurbitacins, although biologically active, are known to exhibit dose-dependent toxicity at high concentrations(Rashid et al., 2023). Therefore, standardization, quality control, and regulatory oversight are essential to ensure consumer safety and build confidence in *C. callosus*-based products.

12.6 Role in sustainable and climate-resilient food systems

The promotion of *Cucumis callosus* as a functional food and nutraceutical resource aligns with broader goals of sustainable agriculture, biodiversity conservation, and climate resilience. Its low input requirements, adaptability to harsh environments, and multiple use values make it well-suited for integration into climate-smart food systems(Boora et al., 2025; Hesham et al., 2020). By bridging traditional knowledge with modern food and health industries, *C. callosus* can contribute to diversified diets, improved nutrition, and sustainable livelihoods in arid and semi-arid regions.

13. Constraints, Knowledge Gaps, and Future Research Directions for *Cucumis callosus*

Despite its long history of traditional use, nutritional richness, and emerging pharmacological evidence, the wider utilization and commercialization of *Cucumis callosus* remain constrained by several scientific, technological, socio-economic, and policy-related challenges. Addressing these limitations is essential for realizing the full potential of this underutilized cucurbit as a functional food, nutraceutical resource, and climate-resilient crop.

13.1 Agronomic and production constraints

One of the primary constraints limiting large-scale adoption of *C. callosus* is the lack of standardized agronomic practices. Cultivation is largely confined to wild or semi-wild populations, rain-fed conditions, and marginal lands, with minimal inputs and limited agronomic management(Boora et al., 2025; Vaghasiya & Ishnava, 2024). As a result, yields are highly variable and dependent on seasonal rainfall and local environmental conditions(Jatav et al., 2016).

Limited availability of improved planting material, absence of released varieties, and inadequate knowledge of optimal sowing time, plant density, nutrient management, and pest control further restrict productivity. Systematic agronomic trials are required to develop region-specific cultivation packages that balance productivity with the species' inherent stress tolerance.

13.2 Genetic erosion and conservation challenges

Although *C. callosus* harbors substantial genetic diversity, increasing land-use change, urbanization, and replacement of traditional food systems pose threats to its natural populations. Genetic erosion of wild and feral populations may lead to irreversible loss of valuable alleles associated with stress tolerance, disease resistance, and nutritional quality (Pandey et al., 2021; Zhao et al., 2021).

In situ conservation of natural populations, coupled with ex situ conservation through seed banks and field gene banks, is critical for safeguarding genetic resources. Comprehensive characterization of existing germplasm using morphological, biochemical, and genomic tools will support conservation and utilization strategies.

13.3 Post-harvest, processing, and value chain limitations

High post-harvest losses, lack of cold-chain infrastructure, and dependence on traditional sun drying limit the quality and marketability of *C. callosus* products. While improved drying and irradiation technologies have demonstrated effectiveness, their adoption remains limited due to cost, infrastructure constraints, and lack of technical awareness among smallholders (Nathawat et al., 2013; Deepika et al., 2023).

Fragmented value chains, inadequate processing facilities, and limited access to markets further hinder commercialization. Development of decentralized processing units, farmer–processor linkages, and capacity-building initiatives is necessary to strengthen value chains and improve economic returns.

13.4 Safety, toxicity, and regulatory gaps

Although *C. callosus* has been consumed traditionally for generations, systematic toxicological evaluations are scarce. Cucurbitacins, while responsible for many of the plant's pharmacological effects, exhibit dose-dependent toxicity at high concentrations, potentially causing gastrointestinal irritation and systemic adverse effects (Deepika et al., 2023).

Key knowledge gaps include the absence of:

- Controlled dose–response studies
- Long-term and chronic toxicity assessments
- Pharmacokinetic and bioavailability data
- Human clinical trials validating efficacy and safety

Such data are essential for establishing safe consumption limits, particularly for concentrated extracts and nutraceutical formulations, and for meeting regulatory requirements.

13.5 Mechanistic and molecular knowledge gaps

While several pharmacological activities of *C. callosus* have been demonstrated in vitro and in animal models, detailed mechanistic insights remain limited. The molecular targets, signaling pathways, and gene–metabolite interactions underlying its antidiabetic, anti-inflammatory, cardioprotective, and anticancer effects are not fully elucidated.

Future research should integrate:

- Transcriptomics, proteomics, and metabolomics
- Nutrigenomic studies linking bioactives to metabolic pathways
- Systems biology approaches to understand synergistic effects of phytochemical mixtures

Such studies will strengthen scientific validation and support evidence-based functional food and nutraceutical development.

13.6 Socio-economic and policy constraints

Limited consumer awareness, perception of *C. callosus* as a "poor man's food," and lack of policy support for underutilized crops restrict its mainstream acceptance. Inclusion of *C. callosus* in government nutrition programs, climate-resilient agriculture initiatives, and biodiversity conservation policies could significantly enhance its visibility and adoption.

Promotion through value-added products, branding, and dissemination of scientifically validated health benefits may help overcome socio-cultural barriers and expand consumer demand.

13.7 Future research directions

To unlock the full potential of *Cucumis callosus*, future research should prioritize the following areas:

1. **Crop improvement and breeding**
    - Development of improved varieties using conventional and genomics-assisted breeding
    - Introgression of stress-tolerant traits into cultivated melon
2. **Standardization of cultivation and processing**
    - Optimization of agronomic practices
    - Development of standardized drying, processing, and storage protocols
3. **Comprehensive safety evaluation**
    - Acute, sub-chronic, and chronic toxicity studies
    - Human clinical trials for functional and nutraceutical products
4. **Mechanistic and nutrigenomic studies**
    - Elucidation of molecular mechanisms of action
    - Interaction of bioactives with metabolic and signaling pathways
5. **Value chain and policy integration**
    - Strengthening farmer–industry linkages
    - Policy inclusion of *C. callosus* in climate-smart and nutrition-sensitive agriculture

14. Conclusion

Cucumis callosus (Rottler) Cogn. represents a uniquely valuable yet underexploited cucurbitaceous species that bridges traditional knowledge systems and modern scientific inquiry. The comprehensive synthesis presented in this review highlights its multifaceted significance as a climate-resilient crop(Hesham et al., 2020), nutritionally rich food source(Boora et al., 2025), genetic reservoir for melon improvement(John et al., 2012), and promising candidate for functional food and nutraceutical development(DEEPIKA et al., 2023).

Botanical and agro-ecological analyses underscore the remarkable adaptability of *C. callosus* to arid and semi-arid environments, supported by morphological traits, physiological resilience, and stress-responsive genetic architectures. Its close phylogenetic relationship with cultivated melon and confirmed placement within the primary gene pool emphasize its importance in crop domestication studies and as a donor of adaptive traits such as drought tolerance, heat resilience, and low-input productivity.

Nutritional profiling reveals that *C. callosus* fruits and seeds provide meaningful contributions of dietary fiber, essential minerals, antioxidant vitamins, and bioactive lipids, aligning well with contemporary dietary recommendations aimed at mitigating non-communicable diseases. The presence of diverse phytochemicals—including cucurbitacins, phenolic acids, flavonoids, carotenoids, and tocopherols—forms the biochemical basis for its reported antioxidant, antidiabetic, antihyperlipidaemic, anti-inflammatory, antimicrobial, and anticancer activities. Importantly, emerging pharmacological evidence offers scientific validation for many traditional ethnomedicinal uses documented across arid regions of India.

Post-harvest handling, preservation, and processing studies demonstrate that appropriate drying, dehydration, and irradiation technologies can substantially reduce losses, enhance shelf life, and preserve nutritional and phytochemical integrity. These advancements, coupled with traditional processing practices such as sun drying and culinary utilization, provide a strong foundation for value addition, rural entrepreneurship, and integration into formal food value chains. The use of *C. callosus* as a natural meat tenderizer further exemplifies its industrial relevance and potential for clean-label food applications.

Despite these strengths, significant gaps remain that constrain the mainstream adoption and commercialization of *C. callosus*. These include limited agronomic standardization, insufficient toxicological and clinical data, fragmented value chains, and inadequate policy support for underutilized crops(Mmbando, 2025). Addressing these challenges will require coordinated interdisciplinary efforts encompassing genomics-assisted breeding, standardized cultivation and processing protocols, rigorous safety evaluations, and supportive policy frameworks.

In conclusion, *Cucumis callosus* embodies the potential of underutilized indigenous crops to contribute meaningfully to sustainable agriculture, nutritional security, and preventive healthcare in the face of climate change and evolving dietary needs. Strategic conservation, scientific validation, and responsible commercialization of this species can unlock new opportunities for climate-resilient food systems while honoring and preserving the traditional knowledge upon which its use has long been founded.

Conflict of interest

We declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work. There is no professional or other personal interest of any nature or kind in any product, service and/or company that could be construed as influencing the position presented in, or the review of our work.

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