

## *Retraction*

# **Retracted: Phytoliths as Emerging Taxonomic Tools for Identification of Plants: An Overview**

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The paper titled “Phytoliths as Emerging Taxonomic Tools for Identification of Plants: An Overview” [1], published in *Journal of Botany*, has been retracted at the request of the author as it was submitted without the consent of the author’s graduate supervisor.

### **References**

- [1] S. Abdul Shakoor and M. A. Bhat, “Phytoliths as emerging taxonomic tools for identification of plants: an overview,” *Journal of Botany*, vol. 2014, Article ID 318163, 9 pages, 2014.

## Review Article

# Phytoliths as Emerging Taxonomic Tools for Identification of Plants: An Overview

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In the recent advancements in identification of plant species, phytoliths have found an immense role in the identification of plants at different levels of taxonomic hierarchy. Many plant groups are known to accumulate silica in solid form in and between the cells and tissues and hence create the structures commonly known as phytoliths. These phytoliths create replicas of the structures where they are deposited. The shapes of phytolith replicas, their size dimensions (morphometric parameters), surface features (ornamentation), distribution, and orientation pattern in epidermal layers of vegetative and reproductive structures as well as their frequency are highly important for characterization of species. Monocotyledonous families particularly the family Poaceae (Gramineae) are known to produce diverse phytolith types that can serve as diagnostic markers for characterization of different taxa at different levels of taxonomic hierarchy. The present paper highlights the importance of phytoliths in taxonomic analysis of plants particularly in the family Poaceae.

## 1. Introduction

Phytoliths are amorphous silicon dioxide ( $\text{SiO}_2$ ) incrustation that occur in and between the cells and tissues of plants. The term phytolith, from the Greek meaning plant stone, has sometimes been used to indicate all forms of mineralized substances deposited by plants, siliceous or calcareous in composition. Examples of the latter are the crystals composed of calcium oxalates, which can be common and diagnostic in cacti and some other dryland plants and have been successfully used to document important aspects of the prehistoric diet [1, 2]. Phytoliths are produced as a result of biological and physical processes by which certain living higher plants deposit solid silica in an intracellular or extracellular location after absorbing silica in a soluble state [monosilicic acid ( $\text{Si}(\text{OH})_4$ )] from the groundwater. After death and decay of the plant, these pieces of silica are deposited into soils and sediments as discrete, microscopic particles of varying sizes and shapes. Because phytoliths are inorganic and thus resistant to the forces of decay that cause the destruction of other types of plant materials, they survive in a well-preserved state over long periods of time. They arguably are

the most durable terrestrial plant fossils known to science. Numerous angiosperms (flowering plants), gymnosperms, and pteridophytes (plants that reproduce asexually by spores) produce large quantities of phytoliths. Not all plant species produce phytoliths; however, an important factor for understanding phytolith production is that patterns of solid silicon accumulation, together with the placement of the hardened deposits in specific tissues and cells of plants, are quite similar in plant species and their most closely related taxa regardless of the environmental conditions of growth [3–9]. In other words, cosmopolitan representatives of temperate zone, arctic, and tropical genera and families demonstrate concordant trends in their phytolith formation patterns. Furthermore, the types of plants that do not seem to target their organs for silicification and thus do not produce appreciable amounts of phytoliths do not do so regardless of where in the world they grow. Some of these nonproducers include aroids (Araceae family), the Amaranthaceae and yams (*Dioscorea* spp.), trees in a number of different families, and most cacti. In many plant taxa, specific cells and tissues representing all the aerial organs are identified as areas designated by the plant for solid silica deposition [7–14]. Examples of where phytoliths

are commonly placed in plants are (1) the epidermis or outermost covering of seeds and fruits from numerous trees and herbs [7, 9, 15–19], (2) subepidermal tissue of orchid and palm leaves [20–22], and (3) the epidermis of the paperlike bracts, called glumes, lemmas, and paleas, which surround and protect grass seeds [23, 24]. A primary reason for this demonstrated consistency in the production and localization of silica is undoubtedly because the presence of silica, both in its dissolved and in its solid states, has numerous, beneficial effects for the growth and development of plants [25]. There is considerable evidence, for example, that one important function of phytoliths is to protect plants from herbivores and pathogenic fungi [11]. It is recognized that plants of a single species can contain different amounts of phytoliths when grown in different environments. It now appears that variable silica content within species has significantly something to do with the production of phytoliths (or of far greater numbers of phytoliths) in places that are not normally targeted by the plant for solid silica deposition [10, 26]. Some of these places are the sheets of polyhedral and jigsaw-shaped epidermal cells that cover the surfaces of tree leaves and layers of bulliform (also called motor) cells that lie primarily on the upper surface of grass leaves and provide places for water storage when they are not silicified [27, 28]. In fact, an excess supply of water in the growing environment and submergence of root systems are directly linked to increased bulliform cell silicification [28]. Conveniently, these are usually the types of phytoliths with the least morphological variability, and they are not normally used to identify plants at any taxonomic level. The previously cited studies and others also indicate that the plants most subject to significant variation in phytolith content are primarily those that would be heavy accumulators of solid silica in any environment.

Difference in silica content among different plant groups is due to local soil and climate conditions that regulate the concentration of plant available silicon (PAS) [29].

## 2. Phytolith Production Patterns and Taxonomic Significance in Plants

Researchers all over the globe found considerable variation in the amount and type of phytoliths in different plant groups. Additionally different structures of plants also vary in terms of quantity of the phytoliths deposited/produced in them. Hence we categorize the phytolith accumulating plant groups (families) into different categories based upon the amount and taxonomic significance of phytoliths produced by them.

### 2.1. Families Where Phytolith Production Is Usually High, Phytolith Types Specific to Family Are Common, and Subfamily and Genus-Specific Forms Also Occur, Sometimes Widely in the Family

2.1.1. *Pteridophytes*. These include Cyatheaceae (tree ferns), Equisetaceae (scouring rushes and horsetails), Hymenophyllaceae (ferns that grow as epiphytes on trees), and Selaginellaceae (forest floor ferns).

2.1.2. *Basal Angiosperms*. These are Annonaceae (sour soup and custard apple), Magnoliaceae (magnolias), Monocotyledons: Arecaceae\* (palms), Bromeliaceae (pineapple family), Commelinaceae, Costaceae, Cyperaceae\* (sedges), Heliconiaceae\*† (banana-leaved Neotropical herbs), Marantaceae\*† (Neotropical forest herbs, *Maranta*, arrowroot), Musaceae\* (bananas), Orchidaceae (orchids), Poaceae\* (grasses, *Zea*, maize, and *Oryza* and rice), and Zingiberaceae\* (the ginger family).

2.1.3. *Eudicots*. These include Acanthaceae, Aceraceae (sugar maple), Asteraceae\* (the sunflower family), Boraginaceae\*, Burseraceae\* (tropical trees), Chrysobalanaceae\* (tropical trees), Cucurbitaceae\* (*Cucurbita* [squashes and gourds], *Lagenaria* [bottle and dipper gourds], *Citrullus* (watermelon), *Cucumis* [cantaloupe and honeydew melons and cucumber], and *Sicana* [cassabanana]), Dilleniaceae, Moraceae\* (breadfruit and jackfruit, figs, and mulberry), Podostemaceae (herbs on rocks in rivers and streams), Ulmaceae\* (elms), and Urticaceae (stinging nettles).

### 2.2. Families Where Phytolith Production

May Not Be High in Many Species Studied but Where Family and Genus-Specific Phytolith Types or Forms Diagnostic of Specific Growth Habits (Trees and Shrubs Marked with #) Occur

2.2.1. *Pteridophytes*. This includes Polypodiaceae (many species of ferns).

2.2.2. *Gymnosperms*. These include Cupressaceae (junipers and cedars), Pinaceae (pines, firs, Douglas fir, and hemlock), Taxaceae, and Taxodiaceae (sequoias and bald cypresses).

2.2.3. *Monocotyledons*. These include Flagellariaceae, Joinvilleaceae, and Restionaceae.

2.2.4. *Eudicots*. These are Capparaceae, Dipterocarpaceae (Southeast Asia tropical trees), Euphorbiaceae\* (rubber, castor oil, and manioc), Fagaceae (oaks, beech, and chestnut), and Flacourtiaceae# (subtropical to tropical trees and shrubs).

### 2.3. Families Where Phytolith Production May Be Common to Abundant in Some Genera but Where Taxonomically Significant Phytoliths Appear to Be Limited in Number

2.3.1. *Basal Angiosperms*. These include Aristolochiaceae (twining lianas), Chloranthaceae, Hernandiaceae, and Piperaceae.

2.3.2. *Eudicots*. These include Combretaceae, Loranthaceae (mistletoes), Menispermaceae, Sapotaceae (sapodilla and star apple), and Verbenaceae (teaks and verbenas).

#### 2.4. Families Where Phytolith Production Varies

*Substantially among Different Subfamilies and Tribes and Forms of Taxonomic Value Appear to Be Limited*

2.4.1. *Eudicots*. These include Clusiaceae, Fabaceae (legumes), Malvaceae (cotton, mallows, and relatives), and Sterculiaceae (chocolate and kola).

#### 2.5. Families Where Phytoliths Have Not Been

*Observed or Where Production Is Often Uncommon to Rare and Is Usually Not of Taxonomic Significance*

2.5.1. *Gymnosperms*. These include Araucariaceae, Cycadaceae (cycads), Gnetaceae, and Podocarpaceae.

2.5.2. *Basal Angiosperms*. These include Myristicaceae, Nymphaeaceae (water lilies), and Winteraceae.

2.5.3. *Monocotyledons*. These include Agavaceae (agaves), Alismataceae (water plantains), Amaryllidaceae, Araceae (taro and *yautia*), Burmanniaceae, Cyclanthaceae, Dioscoreaceae (true yams), Eriocaulaceae, Hydrocharitaceae, Iridaceae, Juncaceae\*\* (the rush family), Liliaceae (onions, garlic, and asparagus), Pontederiaceae, Potamogetonaceae, Smilacaceae, and Triuridaceae.

2.5.4. *Eudicots*. These include Amaranthaceae (amaranths), Apiaceae (carrots), Apocynaceae, Araliaceae, Asclepiadaceae (milkweeds), Bignoniaceae, Bixaceae, Bombacaceae, Cactaceae (cacti), Campanulaceae, Caricaceae (papaya), Cartonemataceae, Chenopodiaceae (chenopods), Convolvulaceae (sweet potato), Ericaceae (heaths), Guttiferae (mamey and mangosteen), Juglandaceae (walnut, hickory, and pecan), Labiatae (mints), Lacistemnaceae, Lauraceae (cinnamon and avocado), Lecythidaceae, Lentibulariaceae, Loganiaceae, Malpighiaceae, Mayacaceae, Melastomataceae, Meliaceae, Myrtaceae, Myrsinaceae, Olacaceae, Oxalidaceae, Pedaliaceae, Polygonaceae, Primulaceae, Proteaceae, Ranunculaceae, Rhamnaceae, Rosaceae, Rubiaceae, Rutaceae, Salicaceae, Sapindaceae, Saxifragaceae, Solanaceae (potatoes, peppers, and tomatoes), Theaceae, Tiliaceae, Typhaceae (cat-tails), Vitaceae, Violaceae, Xyridaceae, and Zygophyllaceae.

The above stated information has been gathered from phytolith studies of modern plant communities from the following parts of the world: (1) general coverage of dicotyledons and monocotyledons [21, 22, 30], (2) North America [3–5, 15, 31, 32], (3) American tropics [17, 18, 20, 33], (4) Subtropical and temperate southern South America [7, 34], (5) the United Kingdom [6, 35], (6) Mediterranean and Alpine Europe [36–38], (7) the Near East [26, 39, 40], (8) Africa [41, 42], (9) Southern China [43], (10) Mainland Southeast Asia [44], (11) New Guinea, other parts of Melanesia, and Oceania [8, 45], (12) northern and central Australia [46–49], (13) New Zealand [13], and (14) subantarctic regions in Campbell Island [50]. \*Reproductive structures (fruits and seeds) also produce high amounts of diagnostic phytoliths.

†Underground organs (roots, corms, rhizomes, and tubers)

may contribute to high amounts of diagnostic phytoliths. \*\*Phytolith production is sometimes more common in inflorescences than in leaves.

It is clear from the above para that great many angiosperms, gymnosperms, and spore-bearing plants, not just the Poaceae and a few other monocotyledonous families, persistently silicify their vegetative and reproductive organs, leading to the production of high amounts of phytoliths with manifold shapes and surface decorations [17]. A significant number of important crop plants make high amounts of phytoliths diagnostic at the genus or species level. This research confirms studies that are during the first-third of the twentieth century in which considerable phytolith production was observed across a wide range of higher plant taxa. Recent studies of plant species from the temperate, tropical, and arctic zones also demonstrate that phytolith production and morphological patterns within and between families are largely congruent and thus these patterns are biologically determined and understandable on a scientific basis. Phytolith analysts can now accurately predict in which families and genera phytoliths are most likely to be found and in which they are least likely to be found. This knowledge facilitates the construction of large modern reference collections for the flora of many study regions because analysts have a good guide for choosing plant species and their individual structures for detailed study. Another notable and well-documented pattern of phytolith production is that angiosperms that contribute to high numbers of vegetative structure phytoliths may also heavily impregnate their seeds and fruits with solid silica. In contrast, angiosperms that do not heavily silicify their vegetative structures produce reproductive structure phytoliths very infrequently.

### 3. Patterns of Silica Deposition and Distribution in Different Plant Structures

Phytoliths not only are useful for taxonomic analysis but also are equally important for archaeological and paleoecological interpretations, so in light of this fact it becomes necessary to understand how overall phytolith production may vary within a plant and to clarify, whenever possible, which phytoliths derive from which plant structures or tissues. As already mentioned, uneven deposition of solid silica within plants and even specific structures is common, so that phytolith formation can be highly localized in a single kind of tissue of a single plant structure. The following patterns have been gathered from studies where different aerial and underground structures of the same or closely related species were assessed for phytolith content. They are presented as general rule-of-thumb guides to phytolith production within plants. Information on domesticated species and important ecological indicator plants is provided where available.

3.1. *Herbaceous Plants*. Studies of reproductive organs show that higher phytolith content may occur in fruits and seeds than in leaves of silicon-accumulating species. Examples include sedges and grasses and the Asteraceae, Cannaceae, Cucurbitaceae, Marantaceae, Musaceae, and Urticaceae [7, 8, 15, 16, 51]. In cereals, the inflorescence bracts, enclosing

the seeds of wheat, oats, barley, rye, rice, and maize, known in botanical terms as glumes, lemmas, and paleas, very often have a higher phytolith content than leaves. The cupules of maize cobs are also a source of considerable amounts of phytoliths. Many of these abundantly produced phytoliths in crop plant and other species are diagnostic at low taxonomic levels. The husks of maize, which anatomically are modified leaf sheaths, generally have low silicon concentrations, with amounts varying between 0.1% and 0.9% [20]. These are values ranging from only one-tenth to one-half of the content of leaf blades, and husk phytoliths do not achieve good representation in soil profiles as often as do leaf and cob remains. With relation to the nonreproductive structures of herbaceous plants, leaves often contribute higher amount of silica (greater than twice) compared to the stems of such plants [52–54]. Stems of species whose leaves do not have a high silicon content correspondingly show little to no production. It has often been assumed, included by the author [20], that most roots and other subterranean organs have a negligible phytolith content. Geis [55] reminded us that, because so little work has been carried out, discussing general patterns is still difficult. It is certainly the case that, in some species rhizomes and tubers, which are underground stems, possess a considerable phytolith content. Examples include the Marantaceae and Heliconiaceae, which are large and important tropical families (unpublished data). Not surprisingly, given that anatomically rhizomes and tubers are vegetative organs, many of the phytoliths are morphologically very similar to those derived from aboveground vegetative tissue, although some of them may be unique to the underground organs and prove useful in identifying these structures in archaeological contexts.

A limited number of studies on silicification patterns in underground structures of grasses from mostly the Panicoideae subfamily have been carried out [55]. Both roots and rhizomes may possess high phytolith quantities. Discrete, identifiable phytoliths appear to be in the minority, although Mulholland [56] isolated silica bodies described as saddle-shaped plus long cell phytoliths from rhizomes and distinctive pitted-plate phytoliths from the roots of three species of Panicoideae grasses. The author believes that Geis's saddle-shaped phytoliths may actually be rondels, types with at least one circular face found in many subfamilies and structures of the Poaceae [54, 57]. Most of the silica described from grass roots is in the form of small, nodular aggregates from endodermal cell silicification whose morphological significance is difficult to assess.

**3.2. Woody Plants.** Detailed studies of phytolith distributions in trees and shrubs are still few, but, on the whole, foliage, fruits/seeds, and, not uncommonly, wood and bark may be expected to have the lion's share of silica. Significant quantities of silica have been isolated from the wood of numerous species of plants [7, 8, 58]. Some species of the Chrysobalanaceae, Moraceae, and Ulmaceae and other families also accumulate large quantities of phytoliths in bark [8]. The earliest studies of phytolith morphology in plants usually did not include reproductive structures, but such work has

become more common during the past 15 years. Piperno's [17] survey of Neotropical species drew attention to the unique phytoliths in fruits and seeds from a wide range of taxa, and work in other parts of the world confirms the patterns originally reported [8, 9]. Among woody plant families so far studied, the Boraginaceae, Burseraceae, Chrysobalanaceae, Ulmaceae, and Urticaceae are notable for the production of these kinds of phytoliths. Distinctive shapes also occur in certain genera of other families where phytolith production is, on the whole, more uneven (e.g., the Euphorbiaceae and Fabaceae). In woody plants, as in herbaceous taxa, production is often restricted to the epidermis of the fruit exocarp and mesocarp (outermost structures surrounding the seeds), where phytoliths probably function to protect the propagules of plants from their predators. In the species studied so far, phytolith production appears to be less common in seeds than in fruits, although many exceptions occur. Morphology is often highly significant in identifying families and individual genera of plants. Seed and fruit phytoliths are often produced by species whose leaves accumulate significant amounts but are almost never present in species showing no or low foliage phytolith production.

#### 4. Phytoliths Types in Family Poaceae and Their Taxonomic Significance

Phytolith research has contributed significantly towards taxonomy of monocotyledons, especially the grass family. Any given grass species produces a wide array of morphologically distinct types of phytoliths, with considerable size variance within each type. An individual phytolith form will rarely provide precise taxonomic identification, although broad group assignment is possible. Prat [59–62] used several microscopic characteristics of the epidermis in describing many grass species. He distinguished three categories of elements in the grass epidermis: (i) differentiated elements, (ii) fundamental elements, and (iii) bulliform elements. Differentiated elements consist of silica cells, exodermic elements (hairs and spicules), cork cells (suberous cells), and stomata. Fundamental elements are epidermal cells that are greatly elongated, parallel to the long axis of the leaf. They are nearly uniform and have few specific characters. By showing the distribution of these three elements in the grass leaf with a dermogram, Prat recognized three subfamilies: Bambusoideae, Panicoideae, and Festucoideae. Brown [30] also used micromorphology in describing 345 genera of grasses. Though stating that the leaf contains the most important diagnostic characters, he warned that (i) minor anatomical variations occur in a single leaf blade, (ii) structural variations occur among leaves from different layers in an individual plant, and (iii) leaves from plants of a single species can also vary among habitats. The diagnostic epidermal characters that he used were shapes of (i) short cells and silica bodies, (ii) macrohairs, (iii) microhairs, (iv) prickle hairs, (v) papillae, (vi) stomata, and (vii) long cells. Metcalfe, like Prat, recognized three major taxonomic groups: (i) Bambusoid, (ii) Festucoid, and (iii) Panicoideae. The bamboos and related genera are clearly distinct from all other

grasses. Using leaf structure, he subdivided the Festucoid and Panicoid groups into several tribes. Siliceous epidermal cells in most grasses are of two distinct sizes, elongate and short. Elongate cells with the long axes parallel to the length of leaf include the “long cells” and interstomatal cells of Metcalfe (Figure 1(a)). Length, wall thickness, and surface ornamentation of long cells are diverse. Ends of interstomatal cells are concave where they fit around stomata, whereas ends of long cells are nearly straight. Short cells are nearly equidimensional and are classed either as “silica cells,” where each is nearly filled with a single silica body, or as cork cells, where they act as cork; however, some cork cells may contain silica. The shape of silica bodies in cells may not correspond to the shape of the enclosing cell. In grass taxonomy, the shape, frequency, and distribution of silica bodies in short cells of the mature leaf are combined with other properties of the epidermis in identifying species and genera.

Twiss et al. [63] proposed three major divisions of short-cell phytoliths corresponding to three dominant subfamilies native to the Great Plains of the United States: bilobate/cross = Panicoideae, saddle = Chloridoideae, and circular/oval/rectangular = Pooideae. They recognized that some deviation from this typology occurred; for example, circular to oval bodies were observed in some panicoid grasses.

Twiss et al. [63] employed shape of silica bodies for determining from which group of grass the phytoliths came. All phytoliths are oriented as they occur in the epidermal cells with the long axis of the leaf horizontal. He categorized phytoliths into four classes based upon their subfamilial affiliations. The Festucoid class contains eight types that are circular, rectangular, elliptical, or oblong. These forms are all geometrically simple and correspond to Prat's [59] subfamily, Festucoideae, that includes four tribes: Festuceae, Hordeae, Aveneae, and Agrostideae, which include the common domestic grasses of the humid regions.

The Chloridoid class consists of only two types of saddle-shaped bodies. Prat [60] described them as “battle axes with double edges” and designated them as a type in the subfamily Panicoideae. Harlan [64], based on phylogenetic relationships, proposed subfamily Eragrostideae that included these three tribes: Chlorideae, Eragrostae, and Sporoboleae. Because saddle-shaped bodies are distinctive and common in atmospheric dust originating in the “short grass” region of the western prairie, hence they should be given equal rank with the other morphological classes.

The Panicoid class contains 11 types that are variations of crosses and dumbbells (Figures 1(d) and 1(h)). Prat [60] described them as halter-shaped and designated them as the eupanicoid type in the subfamily Panicoideae. He included three tribes (Andropogoneae, Paniceae, and Maydeae) in the division. Brown [30] also included Isachneae and Oryzeae in the Panicoid group; their silica bodies are modified dumbbells that cannot be distinguished from other Panicoid forms where they occur as discrete particles. In this class many of the native “tall grasses” of true prairie vegetation exist. Both Prat [60] and Brown [30] recognized that leaves of Bambuseae are distinct from Festucoid and Panicoid leaf types; some genera have silica bodies and other leaf characters

of both types. Prat [59] included a diagram to show that bambusoid silica bodies resembled the Festucoid, Chloridoid, and Panicoid types. In Brown's [30] tabulation of 47 species of Bambuseae, 41 contained saddle-shaped silica bodies, three contained only crosses or dumbbells, and eight contained both Chloridoid and Panicoid types. The only species of bamboo that they examined contained saddle-shaped bodies and was included in the Chloridoid class. Discrete silica bodies from bamboo may not be recognized in soils or sediment. Jattisha and Sabu [65] developed keys for identification of some chloridoid grasses in vegetative stage based on the size, shape, frequency, and orientation of phytoliths in grass epidermis.

The Elongate class contains five types that are diagnostic of the Gramineae as a whole but do not possess any subfamily or tribal characteristics. Elongated silica bodies are from interstomatal cells (Figure 1(a)), whereas others are long cells that have been encrusted or completely filled with amorphous silica (Figure 1(j)). At least some members of this class occur abundantly in all the species studied.

Kerns [31] and Piperno and Pearsall [57] carried out more extensive studies of North American grasses and also found that, despite the three-part division generally held, there were significant deviations from the expected pattern. The same was true of the tropical grasses studied herein. Circular to oval phytoliths or rondels [57], which are most closely associated with the Pooideae, also are found in the Arundinoideae, Panicoideae, and, most prominently, in the inflorescences of the Bambusoideae. Bilobate phytoliths, the most characteristic markers of the Panicoideae, also are present in the Arundinoideae, Pooideae, Bambusoideae, and Chloridoideae [66]. Indeed, bilobates are the most common kind of silica body in phytolith assemblages from certain genera in these subfamilies, such as *Aristida* (Arundinoideae), *Eragrostis* (Chloridoideae), and *Stipa* (Pooideae). Chauhan et al. [67] also found bilobates in some chloridoid grasses (*Cynodon dactylon* L.) in addition to trapezoid types using laser induced breakdown spectroscopy. Similar results were obtained by Shakoore and Bhat [66] in some chloridoid grasses using dry ashing method. The cross shaped phytolith, another panicoid marker, is common in certain Bambusoideae (Olyreae tribe) and occurs in small numbers in the Chloridoideae, Arundinoideae, and Pooideae (*Brachypodium* and *Polypogon*).

Saddle-shaped phytoliths are the dominant phytolith class of the Chloridoideae (Figures 1(b) and 1(c)) [65]. They are also common in two subtribes of the Bambusoideae (Guaduinae and Chusqueinae). Individual genera in the Arundinoideae are marked by highly divergent sets of phytoliths that may exhibit Panicoideae, Chloridoideae, or Pooideae tendencies. Phytoliths with both saddle and bilobate tendencies, called saddle/bilobates, are common in this family, whereas the conventional kinds of saddle and rondel forms are relatively rare. These determinations are consistent with findings that the Arundinoideae is actually a heterogeneous and poorly defined group of loosely related genera [68] and with the current belief that this subfamily is primitive and basal to all others of the Poaceae [69]. It is evident from this analysis that the assignment of short-cell phytoliths found in ancient sediments and fossil plants to a particular

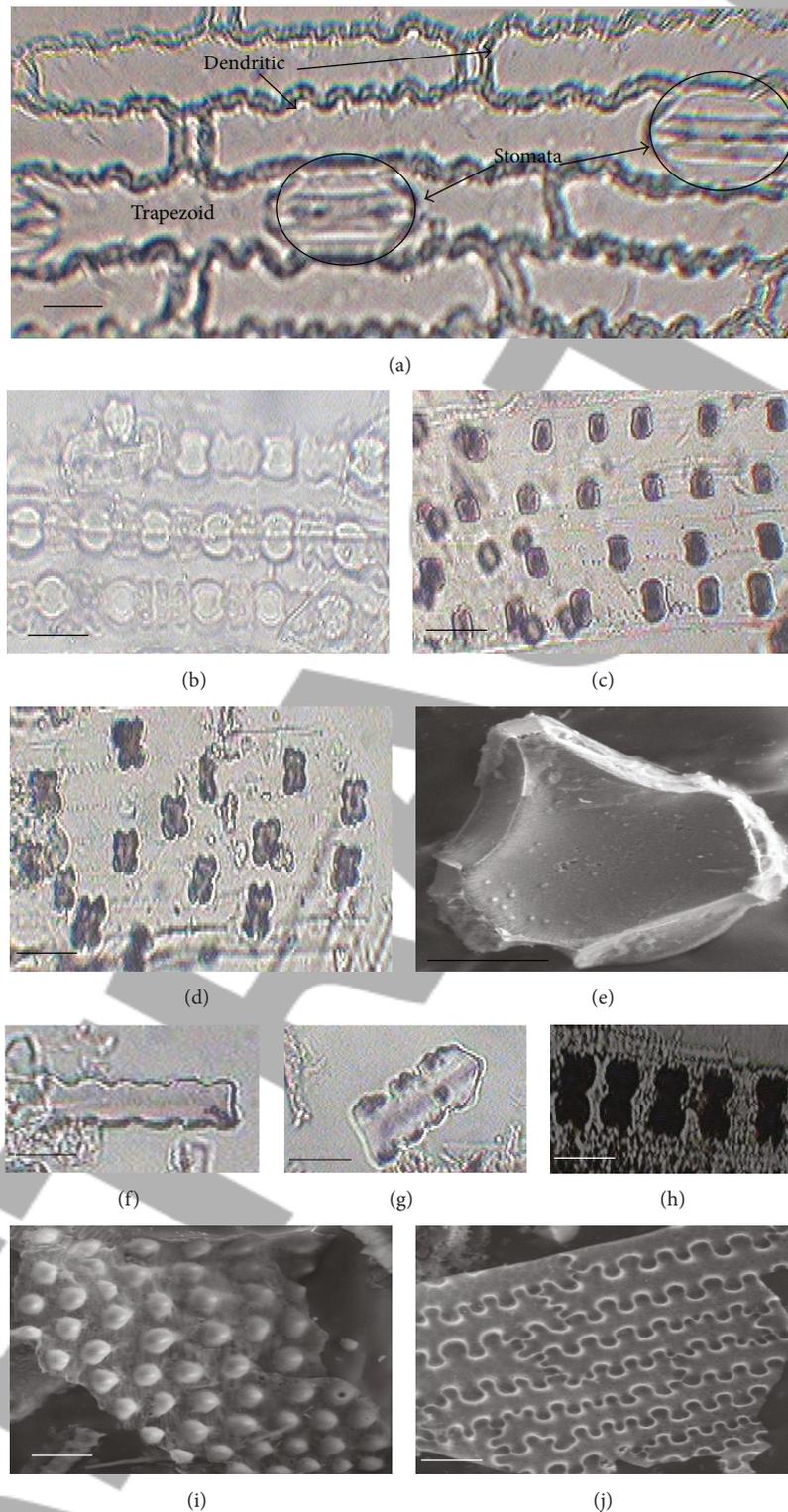


FIGURE 1: Photographs of different phytolith morphotypes: (a) *Hordeum vulgare* (dendritic, stomata, and trapezoids) (bar = 10  $\mu\text{m}$ ). (b) *Desmostachya bipinnata* (saddles) (bar = 10  $\mu\text{m}$ ). (c) *Dactyloctenium aegypticum* (saddles) (bar = 10  $\mu\text{m}$ ). (d) *Lolium temulentum* (crosses) (bar = 10  $\mu\text{m}$ ). (e) *Oryza sativa* (bulliform) (SEM) (bar = 20  $\mu\text{m}$ ). ((f), (g)) *Avena sativa* (sinuate elongates) (elongate types) (bar = 10  $\mu\text{m}$ ). (h) *Oryza sativa* (bilobates/dumb-bells) (bar = 10  $\mu\text{m}$ ). (i) *Panicum antidotale* (prickle hairs/epidermal extensions) (SEM) (bar = 20  $\mu\text{m}$ ). (j) *Digitaria ciliaris* (echinate elongate) (SEM) (bar = 10  $\mu\text{m}$ ).

grass subfamily will not always be possible. Compounding the difficulty is that several different plant structures may contribute to confuser phytoliths. For example, rondels may be found in both the leaves and inflorescences of *Aristida*, whereas saddles occur in leaves, culms, and inflorescences of bamboos. However, a large number of other short-cell phytoliths that were observed in this study do appear to be both disjunct in distribution and diagnostic at and below the subfamily level. Some of them need to be isolated from plant tissue for proper study. Many have not been described previously in other phytolith studies. They also appear to be considerable potential for discrimination of the conventional short-cell phytolith types using microdifferentiation of shape characteristics and phytolith size. Although individual phytoliths often cannot reliably help in classification of taxa, an adequately large sample of phytoliths from a given taxa can be distinguished from closely related taxa through the use of classification keys based on the mean morphometrics of the phytolith sample or the use of the phytolith morphometrics in discriminant functions [70].

## 5. Conclusion

Different plant groups produce diverse phytolith morphotypes. Some of these phytolith types can provide clues for identification of different taxa at different levels of taxonomic hierarchy. Majority of the researchers study phytoliths from leaves only and ignore other plant structures that makes their study less applicable. There is an urgent need to study phytoliths from all plant parts (roots, stem, leaves, and reproductive structures) and must be supplemented with morphometric (size dimensions) as well as frequency data of each phytolith type. Another serious challenge in phytolith systematics is posed by tremendous variations in phytolith shapes between organs, tissues, and cells. Several intrinsic factors seem to control this variation. Stage of plant maturity, intraspecific variation, the rate of leaf transpiration, and the tissue type have been identified as some of the factors. Extrinsic factors like amount of soluble silica in ground water also seem to control levels of silica deposition. There is an urgent need to understand the effect of these variables before one could utilize the full potential of phytoliths as diagnostic markers in plant systematics.

## Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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