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Investigations on the fog harvesting mechanism of Bermuda grass (*Cynodon dactylon*)

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ABSTRACT

Harvesting water from the humidity in air has far reaching advantages to provide access to clean water for consumption, especially in the arid and semi-arid regions of the world. In this regard, fog harvesting properties of a handful of fauna and flora have been explored in the recent past to understand their unique characteristics. In most of the cases, the structural features at the micro- and nanoscales play a crucial role in water collection and transport. In this study, we report the fog collection mechanism in Bermuda grass, *Cynodon dactylon*, which is commonly found in several regions of the world. The fog collection ability of this grass can be attributed to two characteristic structural traits: well-arranged conical spines with sharp edges, wherein the deposition of fog droplets occurs, and hierarchically organized seedheads having flattened surfaces with gradient grooves that transport the coalesced water drop in a directional manner. Both the conical spines and gradient grooves have specified functions in fog interception by virtue of their structural features. The gradient of the Laplace pressure and fiber-like hanging phenomenon of the droplet provide *Cynodon dactylon* with an efficient fog collection system. Further research on the characteristic structural features of this and other similar plants will lead us to the fabrication of bioinspired materials and devices to harvest fog in an efficient manner.

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1. Introduction

Approximately 663 million people *i.e.*, 1 in 10 people, live without access to safe drinking water in different parts of the world and this issue of access to clean water is one of the major global concerns in modern times (UNICEF and Organization, 2015). Interestingly, some indigenous flora and fauna found in many of the arid and semi-arid regions can readily deal with inadequate access to water for survival by collecting water through dew, fog or in general moisture present in the air (Agam and Berliner, 2006; Henschel and Seely, 2008; Schemenauer et al., 1988). Many species have adapted themselves according to the arid regions to increase their chances of survival. Inspired by survival adaptation existing in nature, widespread efforts are being made to exploit fog interception to explore the clean water supply in these water deficit regions (Lekouch et al., 2012; Olivier and De Rautenbach, 2002; Schemenauer and Cereceda, 1991). From the last few years, numerous projects have been initiated in many areas located in the arid and semi-arid climate zones to potentially use fog interception for access to clean water supply (Domen et al., 2014; Fessehaye et al., 2014). The initial research and development done to collect water from atmosphere was based on different types of fog collecting devices, which are known to resist wetting by water and allow condensation to take place leading to the droplet deposition on their surface (Falconer and Falconer, 1980; Schemenauer and Cereceda, 1994). In this conventional method, the droplets increase in size and coalesce with other droplets until eventually these become large enough to get detached from the surface and fall into the collection vessel.

There are many flora and fauna found in several arid and semi-arid regions which harvest dew and fog to cope with their water needs and have led to bioinspired fog harvesting. For example, *Stenocara gracilipes* beetles have micrometer level arrangements of hydrophobic and hydrophilic areas on their backs which capture water from moisture rich air (Parker and Lawrence, 2001). Some plants have also been reported, including *Stipagrostis sabulicola* (Namib bushman grass) and *Cottula fallax*, to capture fog efficiently from the atmosphere and convert it to fresh water utilizing their three-dimensional hierarchical structures (Andrews et al., 2011; Ebner et al., 2011). A multi-structural and multi-functional integrated spine-based fog collection system in cactus has also been shown to demonstrate the natural fog harvesting system (Ju et al., 2012). Different types of cacti species have been compared in a different study and it has been proved that the efficiency of

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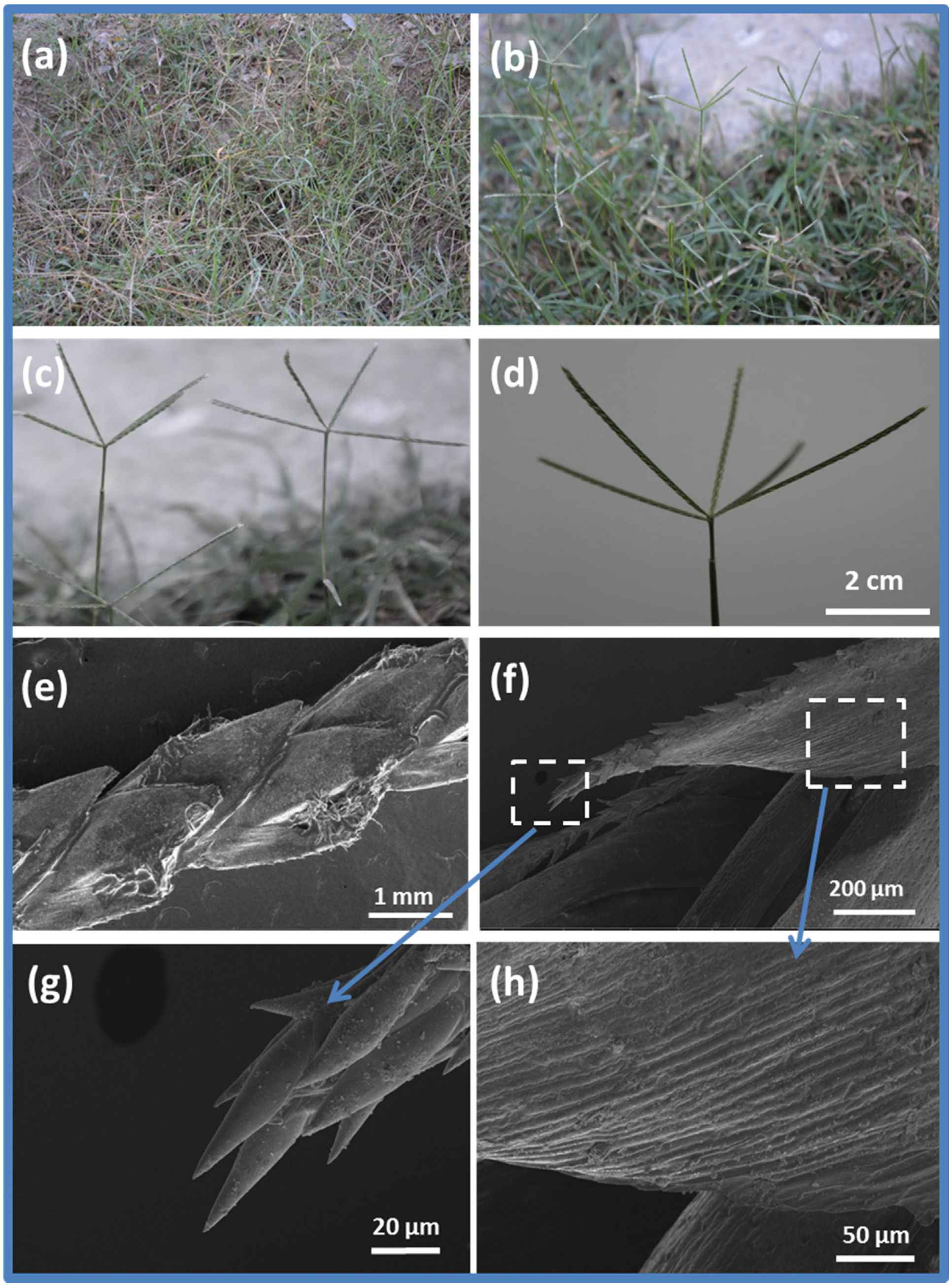

Fig. 1. Morphology and surface appearance of *Cynodon dactylon*: (a and b) Photographs in its natural habitat, (c and d) Images of spikes arranged in the whorl, (e and f) SEM Images showing the microstructures at 1 mm and 200 μm, (g and h) magnified image of spikes having conical spine clusters and gradient grooves, respectively.

the interception of fog and formation of the water droplets from fog is highly dependent on the presence of spines (Malik et al., 2015). In a very recent study, hierarchical surface architecture of *Hordeum vulgare* (barley awns) was found to efficiently harvest fog (Azad et al., 2015). Taking inspiration from these integrated cactus-inspired spine structures and the science of shape gradient-induced Laplace pressure difference, the fabrication of biomimetic systems has been already started to collect fog in an efficient manner (Peng et al., 2015). Spider silks have also been studied to harvest water from moist air (Zheng et al., 2010). The unique fog harvesting capability of the spider *Uloborus walckenaerius* is due to their characteristic fiber structure which includes the naturally occurring periodic spindle knots and joints (Zheng et al., 2010). The gradient of surface-free energy (Chaudhury and Whitesides, 1992) and gradient of Laplace pressure (Bai et al., 2010) have proved to be the main driving forces behind the fog collection system in the spider silk. Inspired by these naturally occurring 'Fog harvesters', biomimetic imitation of naturally occurring fog harvesting structures has become a subject of interest in the scientific community to create new possibilities for maximizing fog-collection efficiency (Dong et al., 2012; Malik et al., 2014; White et al., 2013).

Here we report the fog collection mechanism in Bermuda grass, *Cynodon dactylon*, which is commonly found in several regions of the world. The fog interception can be ascribed to the presence of certain characteristic surface structures possessing specific features for the deposition and growth of water droplets, directional transport of the water droplets, retention and subsequent collection of water droplets. The results have been discussed in detail along with the applicable mathematical formalisms. Research on the characteristic structural features and the underlying mecha-

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