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REVIEW ARTICLE

A tribute to Maarib (Darwish Lutfi Bakri) Bazzaz (1940–2020): the one who proved the existence of "new" chlorophylls in plants

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Abstract We present here a tribute to Maarib Bazzaz (1940-2020), formerly Maarib Darwish Lutfi Bakri, who was an innovative and a highly inquisitive plant physiologist of her time. Her research achievements include exploitation of a highly productive mutant of maize (ON8147), of differences between mesophyll and bundle sheath chloroplasts of maize, and of chlorophyll (Chl) biosynthesis. Above all, she provided convincing scientific proof that, in addition to the usual monovinyl Chl *a* and monovinyl Chl *b*, divinyl Chl *a* (4-vinyl-4-desethyl-Chl *a*) and divinyl Chl *b* (4-vinyl-4-desethyl-Chl *b*) exist in plants. We also include here reminiscences by some of her contemporaries. Particularly noteworthy is how effortlessly Maarib pursued her deep interest in science while raising two wonderful children. She was always curious about life's mysteries and determined to search for answers in a thorough and logical manner. Above all and at all times, she was very kind to others.

Keywords Mesophyll and bundle sheath chloroplasts · Chlorophyll (Chl) biosynthesis in greening plants · Monovinyl and divinyl chlorophyll (Chl) *a* · Monovinyl and divinyl Chl *b* · Olive necrotic mutant of maize · Debunking three light reactions in photosynthesis

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"Let the beauty of what you love be what you do."
– Jalāl ad-Dīn Muhammad Rūmī, a Sufi mystic (1207-1273 CE)

Introduction and early life

We begin this tribute by showing three informal portraits of Maarib Bazzaz (Fig. 1).

Maarib Darwish Lutfi Bakri (Bazzaz) was born on November 27, 1940 in Baghdad, Iraq; her mother was of Turkish origin. She had her early education through the 12th grade, in Baghdad, obtaining her high school diploma in 1956. After completion of her first year of undergraduate studies at the College of Sciences, University of Baghdad, she joined the University of Illinois at Urbana-Champaign (UIUC) to continue her education in 1958.

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Fig. 1 Portraits of Maarib Bazzaz from 1992 until 2019. (Left): 1992, in Hawaii; (Center): 2000, in Boston; (Right): 2019, also in Boston, during a visit of Marilyn and Sanjay Govindjee

Maarib Bakri met Fakhri Bazzaz at the University of Baghdad through friends. The two were married in 1958 in Baghdad (Fig. 2).

Two of us (Rajni and Govindjee), at that time PhD students of Robert Emerson, remember that Maarib was an eager and passionate undergrad in the basic "Genetics" course taught by John R. Laughnan (father of the "super sweet" corn; https://aces.illinois.edu/research/history/supersweet). Maarib completed her BS and MS in Botany at UIUC in 1961 and 1963, respectively. After working for

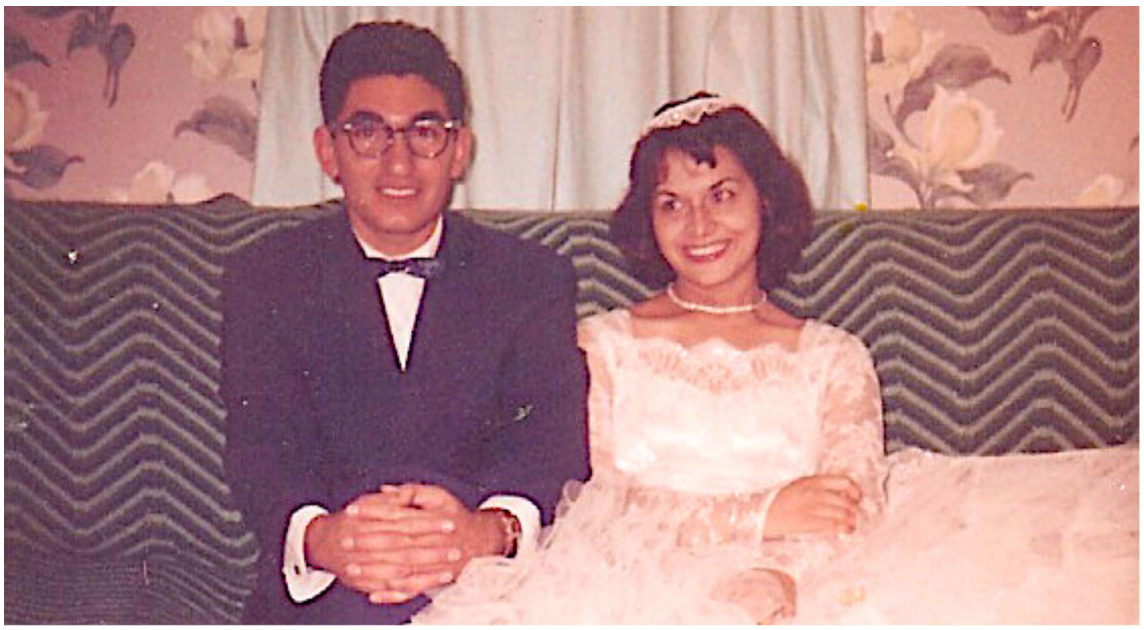

Fig. 2 A 1958 photograph of Maarib and Fakhri Bazzaz after their wedding, in Baghdad; photo provided by Maarib Bazzaz to Govindjee in 2009

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one year as a research assistant at UIUC, she returned to Iraq, together with her husband, and taught Plant Biology for two years at the University of Baghdad, first as a teaching assistant and then as an instructor.

In the fall of 1966, Maarib returned to UIUC and entered the PhD Program in Plant Physiology (an interdisciplinary program in Life Sciences), working as a research assistant in Govindjee's photosynthesis research group. It was a glorious time for the advancement and understanding of the two light reaction scheme of photosynthesis, but everything had to be questioned and checked, including where different artificial electron acceptors pick up electrons in the Hill reaction in chloroplasts. Maarib discovered that the two light effect (the so-called Emerson Enhancement Effect) was present in the Hill reaction in chloroplast fragments with ferricyanide as an electron acceptor (Govindjee and Bazzaz 1967); this meant that even in thylakoid membranes isolated from chloroplasts, existence of two light reactions can be observed with artificial electron acceptors. This research led Maarib to think of going deeper into the question of the overall nature of photosynthesis (for a background on photosynthesis, see Eaton-Rye et al. 2012). She decided to exploit, for her PhD thesis, the use of mutants, particularly of maize for which UIUC was, and, is a great place (http://maizecoop.cropsci.uiuc.edu/mgc-info.php).

Exploiting maize and its mutant, and much more: Doctoral thesis

It was in May, 1972 that Maarib took her final PhD exam in Biology (Bazzaz 1972; her PhD committee included Govindjee (Chair), Charles (Charlie) J. Arntzen, the late Richard (Dick) Hageman, the late James (Jim) F. Nance, and the late Christiaan (Chris) Sybesma (see Vredenberg and Govindjee 2020). Maarib's thesis research, conducted in Govindjee's lab, dealt with (i) a detailed comparison of wild-type maize (*Zea mays*) with an interesting olive necrotic mutant of maize, ON8147, which had a several-fold higher rate of photosynthesis compared to the wild-type; (ii) a thorough and detailed quantitative comparison of mesophyll and bundle sheath chloroplasts of maize; and (iii) a re-examination of the three light reaction scheme proposed at that time by David (Dave) Knaff and Daniel (Dan) Arnon at the University of California at Berkeley.

The most interesting observation in Maarib's PhD research was on the ON8147 mutant (Bazzaz et al. 1974). When compared with the wild-type, the mutant had 4- to 5-fold higher rates of oxygen evolution and electron flow, a much higher ratio of variable to constant Chl *a* fluorescence (indicating higher quantum yield of Photosystem II), and a much lower ratio of total pigments to protein. While each of these results could be explained by a smaller antenna (or photosynthetic unit) size, the mutant had a much higher ratio of Photosystem I (PSI) to Photosystem II (PSII), a finding that remains a bit of a puzzle even today. However, her results (some remain unpublished) provided evidence for remarkable differences in the Chls and Chl–protein complexes between the wild-type and this mutant (see Bazzaz 1972; Bazzaz et al. 1974); her observations were key to the later discovery of a "new" naturally-occurring Chl *a*; see Bazzaz (1981a, b) and the section on 'The new chlorophyll: research at Cambridge, UK'. [For a general background on the biochemistry and biophysics of the Chls, see Grimm et al. (2006), on their role in photoprotection, photoinhibition and regulation, see Demmig-Adams et al. (2008), and for their biosynthesis, see Chen et al. (2018).]

Maarib studied the photosynthetic parameters of chloroplasts in mesophyll and bundle sheath cells of maize; these two types of cells were known to be different in their carbon metabolism (C_3 and C_4), but she showed differences in their "light reaction" components and function. She established that relative to chloroplasts from mesophyll cells, those from bundle sheath cells had a higher amount of long wavelength absorbing Chl *a* forms (Chl *a* 693; Chl *a* 705); a 1.5-fold higher degree of polarization of Chl *a* fluorescence; and a 2-fold lower level of variable to constant Chl *a* fluorescence (for details and implications, see Bazzaz and Govindjee 1973b). These differences remain to be exploited fully even today. Lastly, Maarib's experiments refuted the controversial three light reaction scheme, as proposed by Knaff and Arnon (1969). Maarib (see Bazzaz and Govindjee 1973a) showed that during the prep steps, PSI, by losing long-wave forms of Chl *a*, would look like PSII, suggesting that Knaff and Arnon were using what they called PSII α, not PSI—thus, erroneously concluding that it was an additional, third system. After finishing her PhD, Maarib went on to another project—of environmental concern (see below).

Postdoctoral research: Heavy metals

There was (and still is) a concern for "heavy metals" affecting plant life (see e.g., Tangahu et al. 2011). Maarib examined how cadmium (Bazzaz and Govindjee 1974a) and lead (Bazzaz and Govindjee 1974b) affected the basic reactions of photosynthesis. She showed that although both cations (Pb^{2+} and Cd^{2+}) inhibited electron transport on the (electron) donor side of PSII, lead had additional effects. Further experiments were not pursued as she soon joined the laboratory of Constantin (Tino) Rebeiz (1936–2019; see Govindjee et al. 2020 for a tribute) for studies on the Chls.

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Research on chloroplasts and chlorophylls

We know that Chls are essential for photosynthesis, which provides us food and oxygen to live (Shevela et al. 2018). Tino Rebeiz's laboratory had its focus on Chl biosynthesis (see Govindjee et al. 2020). Maarib had observed interesting differences in Chls between ON8147 and wild-type maize and decided to explore these interests. One of the several research papers Maarib published, while in Rebeiz's lab, dealt with a detailed study of different intermediates of Chl biosynthesis during the greening of cucumber cotyledons when the plants were grown under light and dark regimes (for details, see Cohen et al. 1977). However, Maarib soon became interested in issues dealing with how to exploit "chloroplasts" for the benefit of all of us. Towards this goal, she "cultured" chloroplasts and studied the potential of the repair of degraded Chls in mature chloroplasts which were maintained in a very simple medium (for details, see Bazzaz and Rebeiz 1978). Contrary to the then published reports, she found that "unfortified", fully developed *Cucumis* chloroplasts incubated in Tris–HCl/sucrose, without the addition of cofactors, showed partial and limited Chl repair capability. Most significantly, Maarib was responsible for proving the existence of a "new chlorophyll" (see below).

During Maarib's entire academic career, there was an enormous comradery between the Bazzaz and Govindjee families. Figure 3 shows Maarib with Rajni and Govindjee when Maarib visited their home in the Champaign-Urbana area.

The new chlorophyll: research at Cambridge, UK

In 1981, Maarib independently discovered new Chls *a* and *b* from the ON8147 mutant of maize that she had studied for her PhD thesis (see Bazzaz 1981a, b). Then, she went to work with Richard Brereton, in the Department of Chemistry, University of Cambridge in 1981, and stayed there until the end of 1982. At that time there was considerable interest in the biosynthetic pathways for Chl formation, including their by-products. Substantial development of new structural techniques made possible the elucidation of different structures using what was considered at the time a modern generation of techniques. Maarib developed methods for isolating both 4-vinyl-4-desethyl-Chl *a,* commonly called divinyl Chl *a* (Bazzaz and Brereton 1982; Bazzaz et al. 1982) and 4-vinyl-4-desethyl-Chl *b,* commonly called divinyl Chl *b* (Brereton et al. 1983), which in themselves were quite a challenge. At the time, there were also several pioneering mass spectroscopic techniques becoming available, some of which were in their very early applications, including FAB (Fast Atom Bombardment), FD (Field Desorption) and "In Beam" Electron Impact. In addition, Maarib used another powerful technique, NMR (Nuclear Magnetic Resonance), to look at the structure of the new Chl *a* isomer. These achievements were important and involved not only the knowledge of biochemical pathways, and extraction techniques, but for that time, novel methods of structure elucidation. Further, they led Maarib to prove that indeed plants have both monovinyl and divinyl Chl *a, i.e.*, there are indeed different Chls *a in vivo*!

Maarib's discovery of divinyl Chl *a* continued to be of interest to researchers around the world; see *e.g.,* Goericke and Repeta (1992) for the existence of large amounts of both divinyl Chl *a* and Chl *b* in *Prochlorococcus marinus*, a marine prokaryote; Partensky et al. (1997) for changes in the amount of divinyl-Chl *a/b*-protein complexes, during different growth light conditions, also in *Prochlorococcus*; Wang et al. (2010) for the conversion of divinyl Chl *a* to monovinyl Chl *a* in rice; and, Rodríguez et al. (2015) for the existence of divinyl Chl *a* in a marine eukaryotic protist *Alexandrium ostenfeldii*.

Fig. 3 Two photographs of Maarib in the 1980s. (Left): left to right: Fakhri Bazzaz, Maarib Bazzaz, and Govindjee. (Right): Maarib and Rajni Govindjee enjoying a good laugh together. Source: Archives of the Govindjees

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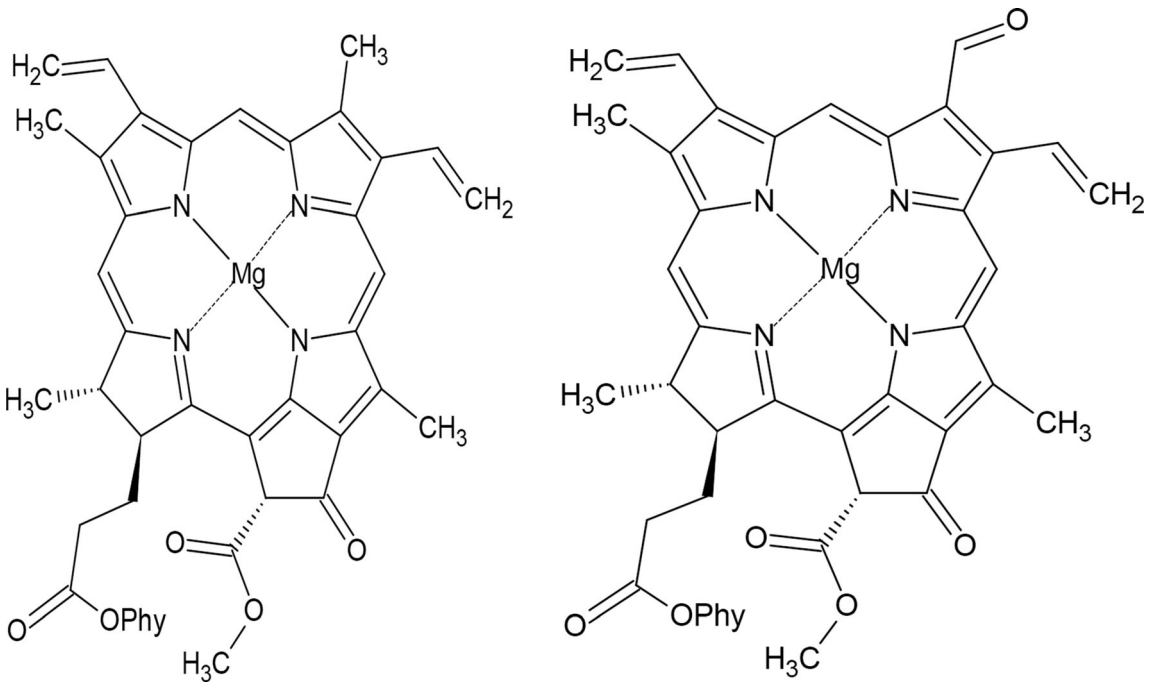

Fig. 4 Chemical structures of 4-vinyl-4-desethyl-Chl *a,* commonly known as divinyl Chl *a* (left) and of 4-vinyl-4-desethyl-Chl *b,* commonly known as divinyl Chl *b* (right)

We note that even before Maarib had proved the different chemical nature of the Chls, differences in spectra were known (see Govindjee et al. 2020, for references to papers from Tino Rebeiz's research group). Further, Freyssinet et al. (1980) showed that different amounts of spectral forms (suggested to be divinyl Chls) were present in different subchloroplast fractions.

Figure 4 shows the chemical structures of 4-vinyl-4-desethyl-Chl *a,* as well as 4-vinyl-4-desethyl-Chl *b.* For details, see Bazzaz and Brereton (1982) and Bazzaz et al. (1982).

Personal reminiscences

We end this tribute with just a few personal reminiscences by Maarib's contemporaries, but first, a quote from Omar Khayyam (1048–1131), a mathematician, a philosopher and a poet, since it reflects what some of us think how Maarib saw things:

"There was a door to which I found no key.
There was the veil through which I might not see…"

We reproduce below four selected reminescences; several others including those from Glenn W. Bedell II and George C. Papageorgiou are available by writing to one of us (gov@illinois.edu). Further, a letter from Maarib's son Ammar to one of us (RG) is reproduced below in a footnote[1].

Charles J. Arntzen (charles.arntzen@asu.edu):
"When I arrived at the University of Illinois as a new faculty member in 1970, my laboratory was located adjacent to the very active Govindjee complex. Maarib was one of his team who helped me find my way around the UIUC system, and to understand the multitude of instruments located in their lab. As my own research team grew in size, Maarib got involved in several projects—in part because we shared strong interests in chloroplast development and also the use of mutant plants to dissect this process. She was a vibrant, inquisitive and generous colleague who was

[1] Upon receiving a letter from one of us (RG): "We are deeply saddened to learn that Maarib succumbed to this nasty virus, which is creating havoc and holding the world hostage, and that we shall not be able to meet her; she was like my younger sister.", Ammar Bazzaz (Ammar@bazzaz.net) wrote: "Dear Rajni: Thank you and Govindjee for your kind words and condolences. As my mother was a little sister to you, you are like a second mother (or very close aunty) to me (and I suspect my sister Sahar feels the same way). I have such fond memories of the times that our families shared while we were in Urbana and it always brings a deeply authentic smile to my face when I think of you, Govindjee, Sanjay, and Anita. I am sorry for your loss as I know how dear she was to you. Let's take solace that she is in a better place, as well as being reunited with my dad Fakhri. Please take care—Be well until then. Kind Regards and Love,—Ammar Bazzaz, President & Engineering Director, Brea, CA www.bazzaz.net."

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very well liked by everyone in my group. Outside the university setting, my wife and I were often at parties with Fakhri and Maarib—they were a truly delightful couple that brightened every gathering. After they departed UIUC for Harvard, we lost contact until I met them again in 2003 on a visit to the Harvard campus—they remained the charming and delightful individuals I remembered. Maarib will be missed by all of us who were a part of the photosynthesis group at Illinois!"

Barbara Zilinskas (zilinska@scarletmail.rutgers.edu): "I'm deeply saddened to learn of Maarib's passing. Two vividly sharp memories come to mind and serve as bookends in my first and last interactions with Maarib. When I joined Govindjee's lab in 1969 as a neophyte graduate student, I was relieved to find another woman in the large lab group filled with men. Maarib was a senior graduate student at that time and a great role model—bright, hard-working and excited about science. However, I particularly remember the days when she came to the lab torn between her commitment to her research and to her young daughter. I recall the tears that she shed as she told me that she was abandoning her sweet child as she worked assiduously at the bench. It wasn't easy to be a young mother and a dedicated researcher at the same time in the early 1970s when daycare didn't even exist. Nevertheless, Maarib deftly learned how to achieve a harmonious work-life balance. My last time with Maarib was about 30 years later. Maarib's beautiful smile caught my eye when we met again at Govindjee's grand retirement celebration, in 1999 (see Fig. 5). Her kindness, elegance and gentle spirit brought back special memories of our earlier days together. I'll truly miss Maarib. My heart bleeds for Sahar and Ammar."

Rita Khanna (khannarita@gmail.com): "I am deeply saddened to hear of the tragic loss of Maarib. I know how close her children, Sahar and Ammar, were to her, and I can only imagine the loss that they must be feeling. I was privileged to have met and known Maarib when I joined Govindjee's laboratory in 1974. Even before I met her, I had heard about her warm personality and keen scientific mind. As I got to know her, I really appreciated her generosity of spirit and willingness to share her insights and candid opinions on science, and life in general. She was an excellent cook and I still remember fondly the hospitality and warmth of the Bazzaz home. She was a dedicated mother to Sahar and Ammar and a wonderful wife and a companion to her husband Fakhri. I remember the story (as relayed by Govindjee) about her PhD thesis exam which happened to be at a time when she was pregnant and due to deliver anytime—and every time she got excited defending her research, the committee members got very nervous. We will all certainly miss her. May her memories and spirit bring comfort to all who knew her at this difficult time."

Mrinmoyee Das (anindyadas2005@gmail.com): "Maarib was a very good friend of mine, and I was known as the Indian "aunty" by her children, Sahar and Ammar. I live in Kolkata (Calcutta), India. Both Maarib and I worked, a long time ago, in "Photosynthesis Lab" at the University of Illinois at Urbana-Champaign. At that time, Maarib was working as a PhD student of Govindjee, and I was a postdoctoral research associate in Eugene Rabinowitch's lab (see Govindjee et al. 2019). Although we did not have any contact with each other after I left the USA, I still have sweet memories of our friendship. Hearing of Maarib's departure was very shocking news to me. *I will never forget her pretty face and soothing personality. She was wonderful to all of us in the lab.* Please accept my deepest condolences on the demise of Maarib. May her soul rest in peace; she will be terribly missed by everyone who knew her."

A *pictorial reminiscence* of Maarib is presented below by two of us (GG and RG) through three group photographs of Maarib, with several different friends at Govindjee's retirement in 1999. Unfortunately, Thomas (Tom) Wydrzynski, one of her contemporaries, another top plant physiologist of his time, is also no more (see Govindjee et al. 2018; Conlan et al. 2019).

Epilog

This epilog will focus on Maarib, the person who she was (based on https://thecommonsinlincoln.wordpress.com/2018/04/09/resident-feature-maarib-bazzaz/). She always spoke clearly and directly to the point. Her oral as well as written communication skills were superb. She was fluent in Arabic. We are told that she spoke Turkish as a child since her mother was Turkish. When Maarib was a graduate student at UIUC, she studied French and Russian. Maarib and Fakhri together traveled extensively, including visits to China, Japan, and many countries in South and Central America and Europe. Many of us know that when Fakhri neared the end of his life, Maarib drove him to far corners of the USA, including Urbana, Illinois, where he had been earlier in his life, so that he could visit with his many friends. This speaks volumes for Maarib's wonderful nature and loving heart.

During the past four years, Maarib lived at "The Commons" in Boston, where she enjoyed many social activities and the comfort provided by the community. There, she enjoyed walking and quilting. Just like many

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Fig. 5 (Top): Maarib with fellow students from her PhD days. Sitting (L to R): Alan Stemler and Maarib Bazzaz. Standing (L to R): the late Thomas (Tom) Wydrzynski, Paul Jursinic, Julian Eaton-Rye, Rita Khanna, Govindjee, and Sunita Christisansen (Govindjee's granddaughter). (Middle): Maarib with other members of Govindjee's laboratory. Left to right: the late Thomas (Tom) Wydrzynski, Alan Stemler, Jin Xiong, Teruo Ogawa, Paul Jursinic, Maarib Bazzaz, Govindjee, Rita Khanna, Barbara Zilinskas, Jack van Rensen, Mary Anne van Rensen, and Julian Eaton-Rye. (Bottom): Left to right: Carole Rebeiz, Maarib Bazzaz, the late Fakhri Bazzaz, the late Constantin (Tino) Rebeiz, Sara Ort, and Donald (Don) Ort. (For Fakhri Bazzaz, see Pickett and Ackerly 2008 and Grubb 2008; and for Tino Rebeiz, see Govindjee et al. 2020)

Americans who came from the far reaches of the globe (UK; Europe; Asia; and the Middle East) and settled in USA, she graciously mastered and negotiated many cultures and languages. She was adept and knowledgeable of the many cultural differences and norms. In one word: Maarib was a wonderful citizen of the world. Unfortunately, and sadly for all of us, she succumbed to the deadly coronavirus, SARS-CoV2. According to her healthcare providers, she was courageous until the end and died peacefully. Maarib leaves behind two wonderful

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Fig. 6 A late 1960s photograph of Maarib, at a picnic; sitting behind her is Fakhri with other friends; this photo was provided by Maarib Bazzaz to Govindjee in 2009

children—who carry the torch of the Bazzaz family. A daughter Sahar, a PhD from Harvard University, is a Professor of History and Middle Eastern Studies, https://www.holycross.edu/academics/programs/historyfaculty/sahar-bazzaz, whereas their son Ammar has his own company—designing and building instrumentation for racing motorcycles https://www.youtube.com/watch?v=8CzZxv9h0BE (see footnote 1).

We end this Tribute by showing a wonderful and lively photograph of Maarib (Fig. 6); this reflects on her friendly attitude to life and people.

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Consent to participate All authors have agreed to participate equally and fully.

Consent for publication All authors have agreed to publish this article in "Plant Physiology Reports".

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