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Comparative Effects of Superhydrophobic Sand and Plastic Mulches on Growth and Yield of Sweet Pepper (*Capsicum annum* L.) under Arid Environments

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Abstract. **Superhydrophobic sand (SHS) is a plastic-free mulching technology that reduces surface evaporation of water from irrigated soils. Here, we present the results of two experimental field trials conducted in the 2019–20 and 2021–22 cropping seasons, comparing the efficacy of SHS with those of traditional plastic mulches on the growth and yield performance of sweet pepper (*Capsicum annum* L.) plants. The experiments were conducted at the King Abdulaziz University (KAU) agriculture research station at Hada Al-Sham (21°48′3″N, 39°43′25″E), Al-Jamoom, Saudi Arabia. The effects of bare soil (i.e., control treatment), 5 mm SHS thickness, and 10 mm SHS thickness, along with white and black plastic mulches (120-μm-thick polyethylene) were recorded on the plants via a randomized complete block design with three replicate plots. We found significant benefits of all of the mulches during the 2021–22 season, as evidenced by 51% ($P < 0.001$), 31% ($P = 0.0102$), and 32% ($P = 0.0048$) more fruits for the 10-mm SHS, white plastic, and black plastic mulches, respectively, compared with the unmulched controls. Consequently, the total fruit yield per plant increased by 112% ($P = 0.000$), 71% ($P < 0.001$), and 83% ($P < 0.001$), under 10 mm SHS, white plastic, and black plastic mulches, respectively. Curiously, the field trial conducted in 2019 in an adjacent field did not reveal significant benefits of SHS, which we attribute partially to erratic rain showers and field heterogeneity. Taken together, this study and our previous work show that 10-mm-thick SHS mulch is optimal for boosting irrigation efficiency in regions where water is a limiting factor. Unlike plastic mulches, SHS biodegrades in <1 year and becomes a part of the sandy soil matrix, thereby obviating landfilling. Thus, the benefits of SHS exceed those of plastic mulches in terms of closing the yield gap and carbon footprint. These findings underscore the potential of SHS as a sustainable solution for growing plants in hot and dry arid regions in Saudi Arabia and globally.**

In arid and semiarid regions of the world, irrigated agriculture claims more than 70% of freshwater withdrawals from groundwater, rivers, and ponds (Fereres and Soriano 2007; WWAP 2014). Due to high solar radiation and direct exposure of the unvegetated bare soils to dry wind, a substantial amount of the irrigated water supplied to soils is lost via evaporation (Alnaizy and Simonet 2012; Balugani et al. 2017; Gong et al. 2017; Lehmann et al. 2018; Verstraeten et al. 2008). In essence, plants and soils in such regions lose tremendous amounts of water because potential evapotranspiration is extremely higher than rainfall received (Fereres and Soriano 2007; Yin et al. 2019).

Covering the interface of plants and moist soil with mulches (i.e., a vapor diffusion barrier) can significantly reduce evaporative losses and enhance irrigation efficiency in water-limited regions (Qin et al. 2015; Zhang et al. 2017). The deployment of mulches for crop production has been proven to enhance the soil moisture content and promote transpiration (Farzi et al. 2017; Zhang et al. 2018), with consequent improvement in plant biomass and yields (Mukherjee et al. 2010; Ramalan and Nwokeocha 2000; Zhang et al. 2017). Conventionally, plastic mulches have been heavily deployed in modern commercial agriculture for reducing the yield gaps between attainable and actual yields for decades (Hillel 1982; Kasirajan and Ngouajio 2012; Qin et al. 2015). Despite their attested yield benefits, plastic mulches (polyethylene sheets) in use, typically in the range of 150 to 500 μm thick, are mechanically fragile and nonbiodegradable, posing huge environmental challenges; for instance, more than 1M metric tons of plastic mulch is landfilled in Western Europe, and the usage is rising in other parts of the world (Barnes et al. 2009; Vox et al. 2016; Wojnowska-Baryła et al. 2022).

Nature-based solutions that are effective, environmentally friendly, and economically viable are needed to boost irrigation efficiency to realize global food–water security (Jury and Vaux 2005). In this direction, biodegradable plastics are being developed, but their cost and time-dependent changes in wetting properties have limited their widespread application (Gross and Kalra 2002; Kasirajan and Ngouajio 2012). Recently, we developed SHS, a new class of nature-inspired mulching technology, composed of common sand grains coated with a nanoscale layer of biodegradable paraffin wax (Mishra et al. 2022). SHS loses its water repellency over time due to the microbial degradation of wax, and the grains get incorporated in the sandy soil. Recently, we demonstrated the potential of SHS for curtailing surface water evaporation and enhancing crop yields under arid conditions via field trials with tomato, wheat, and barley (Gallo et al. 2022); as well as a controlled-environmental study conducted with tomato plants to probe evapotranspiration partitioning and mechanistic insights into plant development (Odokonyero et al. 2022). SHS needs to be tested with different crops under varying conditions of irrigation and soil type to pinpoint its pros and cons.

Here, we report on two field trials of SHS with sweet pepper, which is a major commercial vegetable crop grown in Saudi Arabia due to its pleasant flavor and high ascorbic acid and mineral content (Chávez-Mendoza et al. 2015; Dobón-Suárez et al. 2021). Specifically, the effects of SHS mulch are compared with those of plastic sheet mulches (white and black) relative to the bare controls, on the growth, biomass, and yield performance of sweet pepper (*Capsicum annum*) plants under arid field conditions in Western Saudi Arabia.

Materials and Methods

Location and characteristics of the experimental site. Two field experiments were conducted during the 2019–20 and 2021–22 cropping seasons (from December to April) at the KAU Agricultural Research Station in Hada Al-Sham, Makkah region, Western Saudi Arabia (21.79°N, 39.72°E). The soil is sandy loam with pH 7.8 and electrical conductivity (EC) 1.79 dsm; the soil characteristics are indicated in Table 1.

Plants and soil mulches. Four-week-old seedlings of sweet pepper (*Capsicum annum* L.) cv. California Wonder were procured from a local supplier in Riyadh (Saudi Arabia) and transplanted in the field. We investigated different types of mulches: i) 5 mm SHS, ii) 10 mm

Table 1. Soil physical and chemical proprieties of the KAU Agriculture Research Station at Hada Al-Sham, Al-Jamoom, Saudi Arabia.

pH unit	EC (ds/m)	Sandy loam soil particle size (%)			Organic matter (%)	Organic carbon (%)	Available macro nutrients (%)		
		Sand	Silt	Clay			N	P	K
7.83	1.79	84.21	14.05	1.74	0.453	0.500	0.215	0.070	0.781

Total elements (mg/kg or %)										
Cr	Pb	Ni	Cd	Mn	Fe	Cu	Zn	Ca (%)	Mg (%)	Na (%)
0.11	4.21	0.52	0.06	144.44	239.40	4.78	32.98	1.38	1.15	0.14

EC = electrical conductivity.

SHS, iii) white plastic, and iv) black plastic mulches. Notably, SHS (Fig. 1A; Supplemental Video 1) was manufactured in batch-scale reactors in our laboratory following established protocols (Gallo et al. 2022; Mishra et al. 2022); the plastic mulches (120-μm-thick polyethylene sheets) were purchased from a local store in Jeddah.

Treatments and experimental design. During the 2019–20 season, we tested sweet pepper plants with two thicknesses of SHS (5 and 10 mm) alongside white and black plastic mulch (120-μm-thick polyethylene) and bare (i.e., unmulched) control soils. For the 2021–22 season, we changed the field location within the KAU station and planted the same pepper variety and compared the effects of white and black plastic mulches with the 10-mm-thick SHS layer that we have established as the optimum application rate based on our previous field and greenhouse studies (Gallo et al. 2022; Odokonyero et al. 2022). All the experiments were configured in a completely randomized block design using plots of 2.5 × 2.5 m^2 area with an interplant spacing of 50 cm (Fig. 2). The 2019–20 trial consisted of two blocks each with two replicate plots per treatment involving bare soil, 5 mm SHS, 10 mm SHS, and white plastic mulch, with each plot having 15 plants (n = 30 plants). Meanwhile, the 2021–22 experiment involved four blocks each having four replicate plots completely randomized according to the respective treatments including bare soil, 10 mm SHS, white plastic and black plastic, with each plot containing 20 plants (i.e., n = 80 plants).

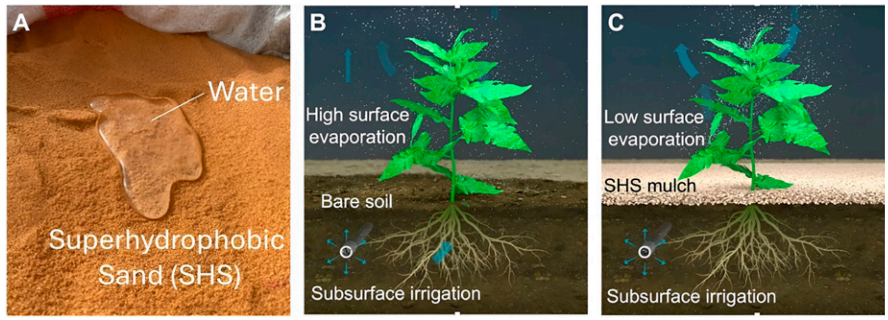

Fig. 1. Superhydrophobic sand (SHS). (**A**) Water repellency of SHS (see Supplemental Video 1 also). (**B**) Under hot and dry conditions, soils suffer from massive evaporative losses, especially when the plants are young. (**C**) SHS presents water from capillary rise, insulating it from direct solar radiation and dry winds. This enhances soil moisture, which can be used by the plant.

Plant growth conditions and data collection. Plants were grown under arid field conditions with normal irrigation (fresh water <1100 ppm) applied twice a day via subsurface drip irrigation system. The irrigation system used was a Rain Bird LD-06-12-1000 Landscape drip, operating at 3.4 L/h per dripping point. All plants were fertilized on a weekly basis by fertigation via the irrigation system using N20–P20–K20 during the vegetative stage and N10–P10–K40 during the flowering and fruiting stages. Plant parameters measured included the total number of fruits per plant, fruit yield (weight) per plant, and the total biomass produced per plant. At maturity, fruits were harvested weekly; fruits were collected in plastic

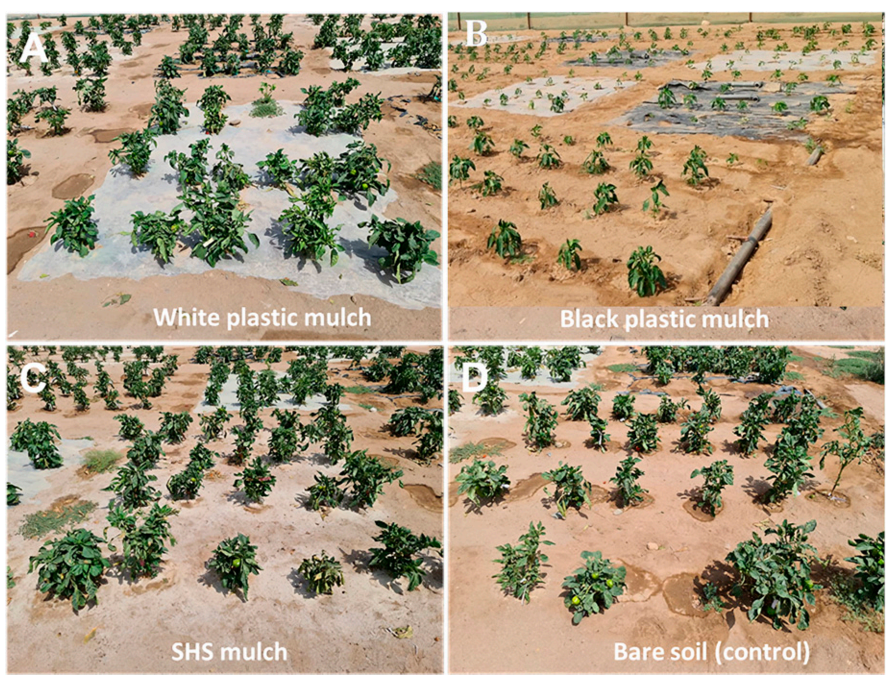

Fig. 2. Snapshot pictures of field experimental plots showing sweet pepper plants grown with different soil mulch treatments at the King Abdulaziz University Agricultural Research Station in Hada Al-Sham, Saudi Arabia (21.79°N, 39.72°E). Sweet pepper plants grown with (**A**) white plastic mulch, (**B**) black plastic mulch, (**C**) superhydrophobic sand (SHS) mulch, and (**D**) unmulched (bare) control soil. Note: subsurface irrigation system deployed.

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H.M. and A.G. have been issued a USPTO patent #11,497,177B2 on 11/15/2022. https://patents.google.com/patent/WO2018091986A1/en.
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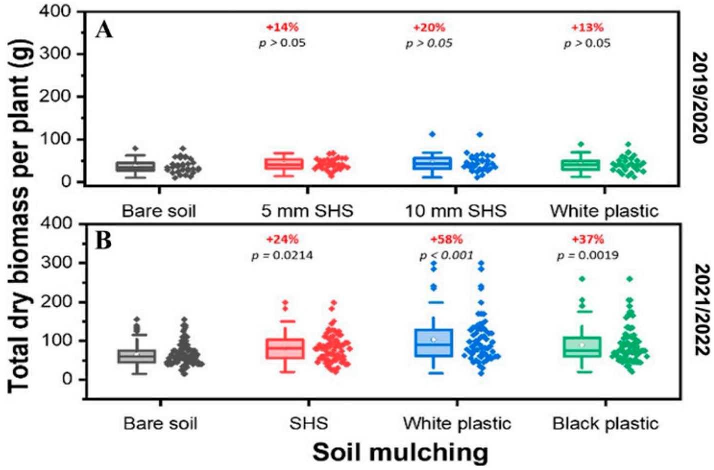

Fig. 3. Box plots showing total dry biomass in sweet pepper plants grown in (**A**) bare soil, 5-mm superhydrophobic sand (SHS), 10-mm-thick SHS, and white plastic (2019–20), and (**B**) bare soil, 10-mm SHS, white plastic and black plastic mulches (2021–22). Each box represents the data distribution from 30 plants (n = 30) for the 2019–20 experiment and 80 plants (n = 80) for the 2021–22 experiment. The midline represents the median, the white dot inside the box represents the mean value, the upper and lower sections of the box represent the 25% and 75% confidence intervals, respectively, the whiskers on the box represent the 1.5 interquartile range. Percentage differences between the bare soil (control) and each treatment are presented along with the corresponding P values derived from post hoc analysis using nonparametric Kruskal-Wallis analysis of variance at $P < 0.05$ level of statistical significance.

bags labeled with the plant identity number, followed by manual counting and weighing using electronic balance. In the 2019–20 season, fruit harvests were conducted for 6 weeks, whereas during the 2021–22 season, fruits were harvested for 7 weeks.

Data analysis. To analyze the fruits and biomass data, we tested the data for normality and performed the nonparametric Kruskal-Wallis analysis of variance in OriginPro software (2020 version). Post hoc analysis was used for multiple comparisons of the means at $P < 0.05$ level of statistical significance. Using the mean values, percentage differences between treatments were calculated and data distribution for each treatment was comparatively presented using grouped box plots. We also performed simple linear regressions (i.e., linear fit of concatenated data) to show the relationships between total number of fruits per plant and total fruit yields in the different treatments.

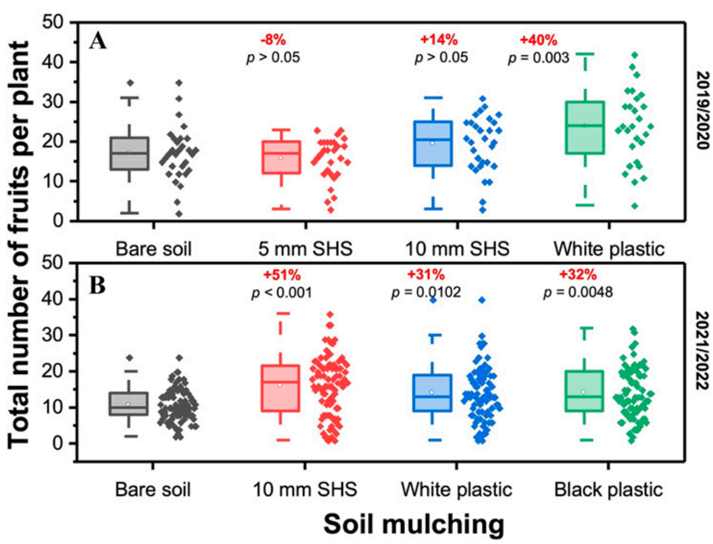

Fig. 4. Box plots showing total number of sweet pepper fruits per plant: (**A**) plants grown in bare soil, 5- and 10-mm-thick superhydrophobic sand (SHS), and white plastic mulches during the 2019–20 season. Each box shows data distribution for 30 samples (n = 30). (**B**) Plants grown in bare soil, 10-mm SHS, white plastic, and black plastic mulches during the 2021–22 season. Each box indicates data distribution for 80 plants (n = 80). The midline represents the median, the white dot inside the box represents the mean value, the upper and lower sections of the box represent the 25% and 75% confidence intervals, respectively, the whiskers on the box represent the 1.5 interquartile range. Percentage differences between the bare soil (control) and each treatment are presented along with the corresponding P values derived from post hoc analysis using nonparametric Kruskal-Wallis analysis of variance at $P < 0.05$ level of statistical significance.

Results

SHS mulch characterization. The combination of sand grains' surface roughness and wax's hydrophobicity rendered superhydrophobicity to the SHS (Fig. 1A), which is characterized by advancing contact angles, $\theta_A \approx 160°$ and contact angle hysteresis $<10°$ for water droplets (Gallo et al. 2022). As water lands on a packed layer of SHS, it bounces and eventually beads up, that is, it does not infiltrate into the SHS layer unless the breakthrough pressure is reached (Supplemental Video 1); also, sand particles may attach at the air–water interface, forming liquid marbles (Gallo et al. 2021). Because SHS blocks the crossflow of water, we used a subsurface system for irrigation (Fig. 1B); albeit, recently, we have figured out a way to use it with standard drip irrigation systems.

Plant growth. For each growing season, sweet pepper plants were cultivated between Dec 2019 and Apr 2020, and Dec 2021 to Apr 2022. Weekly fruit harvests started in late February until final biomass determination in late April of each season (Fig. 2). For the 2019–20 season, erratic episodes of rainfall occurred, which destabilized the SHS applied around each plant (30 cm diameter) leading to some detachment and spread away from the point of application (Fig. 2C).

Total biomass yields per plant. The results indicated that the plant height did not significantly vary across the treatments (data not shown). Data collected on total dry mass per plant for both seasons is presented in Fig. 3. Although total dry biomass in the 2019–20 season was higher for the 5-mm SHS, 10-mm SHS, and white plastic mulches than the controls by 14%, 20%, and 13%, respectively, the differences were statistically insignificant (Fig. 3A). However, during the 2021–22 season, total dry biomass was significantly higher in 10-mm SHS, white plastic, and black plastic mulches by 24%, 58%, and 37%, respectively, compared with the control bare soils (Fig. 3B).

Total number of fruits per plant. In the 2019–20 season (Fig. 4A), there were no significant differences in the number of fruits per plant between 5-mm SHS, 10-mm SHS, and bare soil ($P > 0.05$). However, there was a 40% increase in total number of fruits per plant when white plastic mulch was used compared with the bare soil ($P = 0.003$). During the 2021–22 season (Fig. 4B), there were significant effects of all mulches as evidenced by 51% ($P < 0.001$), 31% ($P = 0.0102$), and 32% ($P = 0.0048$) more fruits in 10-mm SHS, white plastic, and black plastic mulches, respectively, than in the bare soil.

Total fruit yields per plant (g). For the 2019–20 season (Fig. 5A), fruit yields per plant increased by 46% under white plastic mulch relative to the bare soil ($P < 0.001$) but no significant yield increase was observed for 5-mm and 10-mm SHS mulches relative to the bare soil. In the 2021–22 season, however, significant effects of all mulch

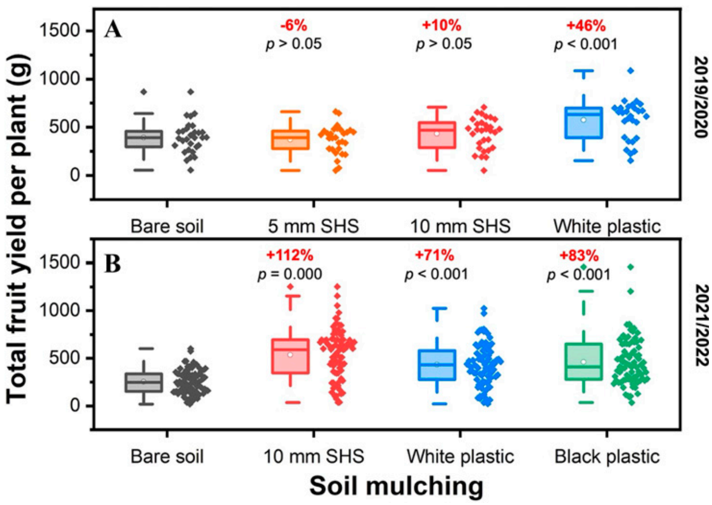

Fig. 5. Box plots showing total fruit yields per plant under (**A**) bare soil, 5-mm and 10-mm-thick superhydrophobic sand (SHS), and white plastic (2019–20), and (**B**) bare soil, 10-mm SHS, white plastic, and black plastic mulches (2021–22). Each box represents the data distribution from 30 plants (n = 30) for the 2019–20 experiment and 80 plants (n = 80) for the 2021–22 experiment. The midline represents the median, the white dot inside the box represents the mean value, the upper and lower sections of the box represent the 25% and 75% confidence intervals, respectively, the whiskers on the box represent the 1.5 interquartile range. Percentage differences between the bare soil (control) and each treatment are presented along with the corresponding P values derived from post hoc analysis using non-parametric Kruskal-Wallis analysis of variance at $P < 0.05$ level of statistical significance.

types were observed; total fruit yield per plant increased by 112% ($P = 0.000$), 71% ($P < 0.001$), and 83% ($P < 0.001$), under 10-mm SHS, white plastic, and black plastic mulches, respectively, compared with the bare soil (Fig. 5B).

To establish the association between sweet pepper fruit parameters in the two seasons, a simple linear (Pearson) regression was performed that demonstrated strong positive relationships between total number of fruits per plant and fruit yields per plant in each cropping season (Fig. 6). The higher the number of fruits per plant, the higher the yield per plant.

Discussion

The deployment of conventional plastic mulches in agriculture is known to boost crop yields, but its environmental impact is concerning (Kasirajan and Ngouajio 2012). This study demonstrates that mulching with SHS can help close the yield gap, at par with plastic mulches, but without landfilling pollution (Zhang et al. 2017). Over time, the soil bacteria consume the wax coating and SHS is reduced to sand grains that become a part of the sandy soil (>90% sand content). That is, the physical, chemical, or biological properties of the sandy soil remain the same after SHS is consumed by the soil system (Gallo et al. 2022).

Next, we discuss the contrasting results from the two cropping seasons of sweet pepper plants (i.e., 2019–20 and 2021–22), in terms of dry biomass, number of fruits, and fruit yields per plant (Figs. 3–5). Whereas SHS and plastic mulch treatments showed significant benefits in the 2021–22 season, SHS treatments did not show significant results in the 2019–20 season for all measured variables. We attribute it to the spatial variability between the two fields and splash erosion from erratic rainfall events during the 2019–20 season that disturbed the SHS layer and reduced its efficacy. As shown in Fig. 2C, although the SHS was initially applied in 30-cm diameter around the plant roots, the heavy rain led to the movement and spread of the SHS within the plots. Studies have shown that splash erosion can cause significant surface deformation and large soil losses on hydrophobic agricultural soil (Ahn et al. 2013; Doerr et al. 2000; Müller et al. 2018; Sochan et al. 2023). SHS (or any other mulch) boosts plant yield and biomass under limited water conditions. Consequently, as soil moisture became less of a limiting factor during the 2019–20 study, the efficacy of SHS mulches reduced. We hypothesize the beneficial effects shown by white plastic mulch may be due to its mechanical integrity against rainfall events and heat transfer characteristics. We plan to investigate the heat transfer effects of mulches at the soil–plant–air interface in the future.

The results of the growing season 2021–22 demonstrate significant beneficial effects of all mulch types with significant increase in total biomass, fruit number, and fruit yields. However, 10-mm SHS mulch proved to be more efficacious with nearly double the number and yields of fruits as compared with the white and black plastic mulches (Figs. 4B and 5B). Enhanced soil moisture due to SHS or plastic mulches, transpiration fluxes increased due to high stomatal conductance arising from the opening of the stomatal aperture in the mulched plants (Odokonyero et al. 2022; Pantin and Blatt 2018). Consequently, rate of photosynthesis increases resulted in increased plant growth, biomass, and yields (Condon et al. 2004; Haefele et al. 2009).

As selection criteria for improving crop yields, both the number and mass of fruits are used as relevant parameters (Kousar et al. 2021; Monamodi et al. 2013). Using Pearson's linear regressions, strong positive correlations were found between the number of fruits and total fruit yield (mass) per plant, for both the 2019–20 (Fig. 6A, $P < 0.001$)

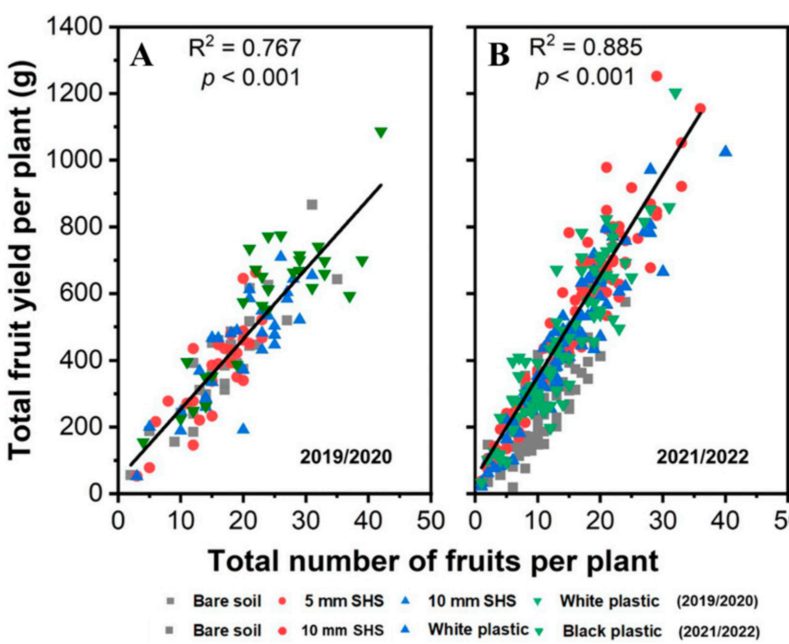

Fig. 6. Simple linear regressions showing strong relationships between total fruit yield and number of fruits per plant: (**A**) Linear fit of concatenated data for total fruit yields vs. total number of fruits per plant in bare soil, 5-mm superhydrophobic sand (SHS), 10-mm-thick SHS, and white plastic from the 2019–20 planting season, and in (**B**) bare soil, 10-mm SHS, white plastic and black plastic mulches for the 2021–22 season. Each data point represents individual plant, with each treatment having 30 samples (n = 30) for the 2019–20 experiment and 80 plants (n = 80) for the 2021–22 experiment.

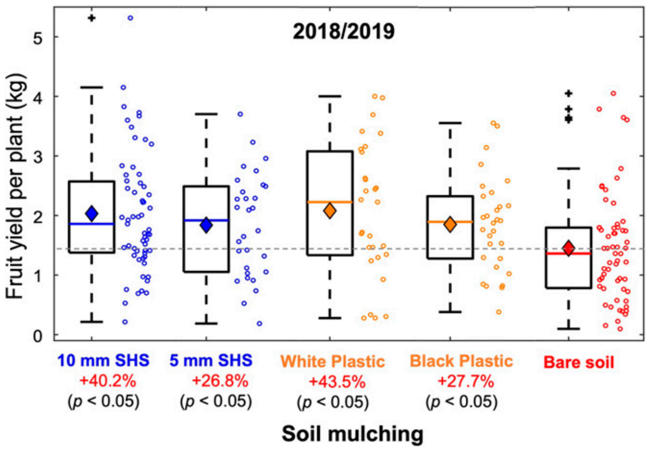

Fig. 7. Effects of superhydrophobic sand (SHS) and plastic mulches on tomato (variety Bushra) fruit yields in 2018–19 field trials at the King Abdulaziz University Agricultural Research Station in Hada Al-Sham, Makkah region, Western Saudi Arabia (21.79°N, 39.72°E). Results for tomato yields under 5- to 10-mm SHS mulches (blue) vs. bare soil (red) and white and black plastic mulches (orange) vs. bare soil. SHS mulches significantly increased the yields of tomatoes. Dots in the boxplot represents the measurements for individual plants from replicate plots. The fruit yield was collected over a period of 6 weeks with the total yield per plant shown in each dot. The boxes contain the middle 50% of the data points, with the horizontal line indicating the median and the diamond inside the box indicating the mean; each treatment was compared relative to the control (bare) case using Kruskal-Wallis H test at $P < 0.05$ for statistical significance and the percent change is the relative difference of the means. This result is adapted with permission from (Gallo et al. 2022).

and 2021–22 seasons (Fig. 6B, $P < 0.001$). This association implies that, as more fruits are produced per plant, fruit mass per plant also increases, thus accounting for overall increase in yields (Ara et al. 2009). However, the relationship was stronger in the 2021–22 season ($R^2 = 0.885$) than in the 2019–20 season ($R^2 = 0.767$).

In Fig. 7, we present our previously published results of a study of the effects of SHS and plastic mulches on a tomato crop (2018–19 season, also from the KAU field station in Hada Al-Sham). Significant enhancements in tomato fruit yields were recorded due to 5-mm SHS (+27%), 10-mm SHS (+40%), white plastic (+44%), and black plastic mulches (28%). These results are consistent with the observed positive yield effects in sweet pepper plants using 10-mm SHS, white plastic, and black plastic mulches during the 2021–22 season, as presented in Fig. 5B.

Conclusion

Taken together, the results of this study demonstrate that SHS mulch application could significantly benefit crop yield improvement in arid regions, equaling or even surpassing the yield performance with plastic mulches, as also validated in recent multiyear studies (Gallo et al. 2022). Unlike plastic sheets that persist in the environment, SHS mulch becomes the part of the sandy soil in ∼1 year, obviating landfill pollution. This nature-inspired technology is expected to contribute to sustainable food production and greening projects Saudi Arabia, the Middle East, and arid lands globally.

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