MITIGATING CARBON DIOXIDE EMISSION USING NINETEEN TREE SPECIES IN THE GREENBELTS OF CEMENT FACTORIES IN EGYPT

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Abstract. The cement industry is responsible for approximately 8% of planet-warming carbon dioxide emissions. Establishing greenbelts around cement industrial areas may be an effective strategy to reduce atmospheric CO_2 pollution. Thus, the main objective of this study is to identify high-performing tree species in carbon sequestration under ambient and elevated carbon dioxide conditions to be used for mitigating cement pollution in Egypt. Hence, we chose 19 tree species for this purpose. The CO_2 response curves (A/C_i response curves) and leaf gas exchange parameters of each tree species were measured using a portable photosynthesis system (LCpro-SD). Rubisco activity and electron transport chain activity were calculated for each tree species. At CO_2 concentration up to 800 ppm, only six species exhibited tight relationships between photosynthetic rate and intercellular CO_2 (C_i): *Conocarpus lancifolius, Delonix regia, Populus alba, Dalbergia sissoo,* and *Ficus infectoria* and *Senna surattense*. The total stomatal conductance was elevated in *D. sissoo, D. regia,* and *Morus alba*. While, *Azadirachta indica* and *P. alba* showed the highest water-use efficiency at the same conditions. The highest Rubisco activity (45.6 to 43.5 μmol m^{-2} s^{-1}) was recorded at 800 ppm CO_2 for *P. alba*, *Duranta erecta*, *D. regia, S. surattensis*, *S. sesban*, and *F. infectoria*. Accordingly, we recommend the cultivation of *D. regia* and *P. alba* in the greenbelts of the cement factories and urban areas to sequester more CO_2, and help in mitigating the impact of climate change. More research is advised under field-scale validation or long-term monitoring in local environmental circumstances.
Keywords: *industrial area, intercellular CO_2, Rubisco activity, photosynthetic rate, urban trees*

Review of literature

An exponential increase in the concentration of greenhouse gases (GHGs) is expected to pose several threats related to climate change over the next 100 years. One of the GHGs is carbon dioxide, whose emissions are projected to increase by 4% by 2050 (Khaiyum et al., 2023). The cement industry is one of the many sources that releases carbon dioxide into the atmosphere. Cement manufacturing is a growing industry that contributes

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significantly to carbon emissions (Khaiyum et al., 2023). Egypt increased cement production from 4 million metric tons in 1975 to 46 million tons in 2009, accounting for approximately 1.5% of global cement production (EEAA, 2010). In 2018, Egypt's cement production was considerably higher than expected at 81 million metric tons (Egypt-cement production 2019 | Statista). Carbon dioxide is produced as a byproduct of clinker synthesis, in which calcium carbonate is converted to calcium oxide (lime) as a major component of cement. Cement manufacture emits CO_2 due to fossil fuel burning (Intergovernmental Panel on Climate Change (IPCC), 1997). Several proposals can be used to reduce carbon dioxide in cement production areas, such as the reduction of energy-related emissions, clinker production improvement, and the development of carbon capture, consumption, and storage methods (Habert et al., 2010; An et al., 2019**)**.

Natural ecosystems play an important role in mitigating the impacts of climate change. Planting trees is a solution for removing CO_2 from atmospheric air and assimilating it into plant biomass *via* the vital process of photosynthesis (Griscom et al., 2017; Turner, 2018). Long-lived olive trees are projected to sequestere amount of 0.22 Gt CO_2, which is considered a carbon stock that may be protected and enhanced by applying some creative olive-farming practices (Gal´an-Martín et al., 2022). Urban and forest trees have been found to be effective for carbon sequestration in polluted and non-polluted areas (Osman et al., 2023; Sprengel et al., 2023; Yao et al., 2023).

Photosynthetic responses to CO_2 represented by A/Ci curves are used to study the photosynthesis reactions rate to environmental changes (Slot and Winter, 2017). As these curve data are associated with leaf metabolism and biochemistry through Farquhar et al.'s (1980) classical model, by computing, they are used to calculate the biochemical restrictions on photosynthesis. For example, calculating the maximum rate of Rubisco carboxylation (Vcmax) and the maximum rate of electron transfer to CO_2 (Jmax) (Stinziano et al., 2019). So, A/Ci curves can be an applicable tool to predict the behavior of trees with elevated levels of CO_2 in the atmosphere, especially in cement factory zones. The establishment of a Ci threshold (Ci-t*) before the curve exchanges between the Rubisco-and electron transport-restricted parts is necessary to determine leaf photosynthesis and gas exchange using A/Ci curve regression analysis (von Caemmerer and Farquhar, 1981). Long-standing exposure of C3 plants to elevated CO_2 may result in the acclimation of plants to high activity, consequently, this can maximize metabolic efficiency (Leakey et al., 2011).

The establishment of greenbelts around industrial/urban settlements is a cost-effective solution to the problem of air pollution (Elawa et al., 2022). The design of greenbelts in an appropriate scientific manner not only reduces air pollution but also sequesters carbon dioxide, reduces noise pollution, provides habitat for wildlife, and enhances the aesthetic appearance (Shannigrahi et al., 2003). Greenbelts in industrial areas are designed mainly to reduce particulate matter and noise pollution (Rane, 2010). However, considering the climate change and global warming caused by industrial greenhouse gas emissions, carbon sequestration in forests and agricultural land has become important (CPCB, 2016). The species used in greenbelts should be tolerant of air pollution. The levels of air pollution tolerance vary from species to species, depending on the ability of the plant to withstand the effects of pollutants without causing any external damage (Rao et al., 2004).

Finally, we hypothesized that not all tree species will perform evenly under elevated CO_2 concentrations. Moreover, the identified high-performing tree species in carbon sequestration will be potential candidates for greenbelts around the cement factories. Therefore, this study aimed to determine which of the 19 common street trees has the

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most effective carbon sequestration potential under different concentrations of CO_2 (50-800 ppm), assuming their future use as greenbelts under elevated CO_2 conditions around cement factories. For this purpose, the photosynthetic capacity (A) and its parameters, along with the A/Ci response curves and Rubisco activity are the measured parameters for the tested tree species under a range of CO_2 concentrations.

Materials and methods

Assessment of common tree species for C-sequestration

To recommend several common tree species in Egyptian local nurseries for cultivation at the greenbelts of cement factories based on their ability to sequester CO_2, we selected 19 tree species (*Table 1*). All the selected trees were mostly characterized by maturity by big green vegetation, evergreen or deciduous for a short time, adapted to the Egyptian environment, and fast-growing. The tree species used in this experiment ranged from two (potted, 13 species) to approx. twenty years old (cultivated, 6 species) years old, with three replicates for each. We had to use the old cultivated species in this study because the two-year seedlings were not available during the time of measurements.

Table 1. *List of the studied tree species for their CO_2 sequestration potential*

No	Tree name	Family name	English name	Age (years)
1	*Cassia nodosa* Bos.	Fabaceae	----------	≈ 20
2	*Dalbergia sissoo* Roxb. ex DC.	Fabaceae	Indian Rosewood	≈ 20
3	*Ficus infectoria* Roxb.	Moraceae	----------	≈ 20
4	*Khaya senegalensis* (Desv.) A.Juss.	Meliaceae	Senegal mahogany	≈ 20
5	*Senna surattensis* (Burm. f.) Irwin & Barneby	Fabaceae	Glaucous Cassia	≈ 20
6	*Sesbania sesban* (L.) Merr.	Fabaceae	Common Sesban	≈ 20
7	*Azadirachta indica* A. Juss.	Meliaceae	Indian lilac	2
8	*Bauhinia variegate* L.	Fabaceae	Camel's Foot	2
9	*Conocarpus lancifolius* Engl.	Combretaceae	----------	2
10	*Delonix regia* (Bojer ex Hook.) Raf.	Fabaceae	Flamboyant	2
11	*Duranta erecta* L.	Verbenaceae	Golden dewdrops	2
12	*Eucalyptus camaldulensis* Dehnh.	Myrtaceae	Murray red gum	2
13	*Ficus nitida* Thunb.	Moraceae	----------	2
14	*Morus alba* L.	Moraceae	white mulberry	2
15	*Mimosa pigra* L.	Fabaceae	Black mimosa	2
16	*Morus macroura* var. *alba* Miq.	Moraceae	----------	2
17	*Populus alba* L.	Salicaceae	White Poplar	2
18	*Syzygium cumini* (L.) Skeels	Myrtaceae	Java plum	2
19	*Tecoma stans* (L.) Juss. ex Kunth	Bignoniaceae	Yellow trumpet bush	2

A/Ci response curves

The CO_2 photosynthetic or net assimilation rate (A)/intercellular CO_2 (C_i) response curves (A/C_i response curves) were measured for each tree species (n = 3). The leaf gas exchange of each species was measured using a portable photosynthesis system (LCpro-SD, ADC Bio Scientific, Hoddesdon, UK) equipped with a standard broad leaf chamber (2 × 3 cm^2), a CO_2 injector, and a red/blue LED light source. The pots of all

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replicates were well watered a day before measurements to a level of moisture capacity (0.7 L) of a pot. On the other hand, the cultivated species were sampled from Helwan University, where they are cultivated few meters away from the measurement site of the potted trees. The cultivated trees were well-watered a day before measurements, and the measurements were carried out on fully expanded leaves from 9:00 am to 1:00 pm.

During measurements, nine concentrations of CO_2 (C_a) (ambient, 300, 200, 100, 50, 100, 500, 650, and 800 ppm) were supplied via the LCpro-SD CO_2 injection system. PAR was maintained above 600 μmol m^{-2} s^{-1}, the flow rate was fixed at 200 μmol s^{-1}, and the block temperature was 25 °C. The net CO_2 assimilation rate (A), stomatal conductance (g_s), transpiration rate (E), and intercellular CO_2 concentration/ambient CO_2 ratio (C_i/C_a) were estimated from gas exchange measurements using equations developed by von Caemmerer and Farquhar (1981). To eliminate the possible effects of air humidity and temperature on transpiration, intrinsic water use efficiency was calculated as the ratio of A to g_s (Iacono et al., 1998).

Water use efficiency (WUE, μmol CO_2 $mmol^{-1}$ H_2O) was calculated using the ratio of A/E to eliminate the possible effects of air humidity and temperature on transpiration. The resulting A/C_i curves were fitted according to Tezara et al. (2003).

The initial slope of the A/C_i response curve (C_a at 50, 75, 100, 200, and 400 ppm) represents the carboxylation efficiency of the plants (Farquhar and Sharkey, 1982). The resulting A-C_i curves were fitted to the equation $A = a + be^{kCi}$, where a is the CO_2-saturated photosynthetic capacity and ($a + b$) is the A-intercept (Tezara et al., 2003). The CO_2 compensation point is the CO_2 concentration at which A is zero.

Rubisco activity, Triose phosphate utilization, and electron transport

Photosyn Assistant software (version 11) was used to determine PAR-saturated rate electron transport (Jmax), rubisco activity (Vcmax), and triose phosphate utilization (TPU) using photosynthetic activity, photon flux density, and leaf temperature parameters for each tree species. The program uses the model proposed by Farquhar et al. (1980), as subsequently modified by von Caemmerer and Farquhar (1981), Sharkey (1985), Harley and Sharkey (1991) and Harley et al. (1992).

Results

Photosynthetic activity

Under ambient air conditions, net photosynthesis (A) showed high variability among the selected tree species (*Fig. 1*). Regardless of the plant age, the highest A values (μmol m^{-2} s^{-1}) were recorded for *Dalbergia sissoo*, *Ficus infectoria*, *Delonix regia*, and *Conocarpus lancifolius* (19.76, 12.96, 12.46, and 12.53 μmol m^{-2} s^{-1}, respectively). The maximum total stomatal conductance (gs) was in *Bauhinia variegata* and *F. infectoria* (289.7 and 266.5 mmol m^{-2} s^{-1}). The transpiration rate (E) was remarkably high in *F. infectoria*, *Morus alba*, and *B. variegata* 3.95, 3.58, and 3.57 mmol m^{-2} s^{-1}, respectively, while the lowest value was recorded for *K. senegalensis* (0.32 mmol m^{-2} s^{-1}, *Fig. 1*). Accordingly, the intrinsic water use efficiency (A/gs) was maximum in *K. senegalensis,* which had the lowest intrinsic CO_2 concentration (C_i) and C_i/Ca ratio. The highest C_i concentrations were recorded for *M. macroura*, *F. nitida*, and *T. stans* (428.2, 397.8, and 379.1 μmol mol^{-1}, respectively). The range of most Ci/Ca ratios was 0.6-0.8, with a maximum value of 1.3 for *D. erecta*.

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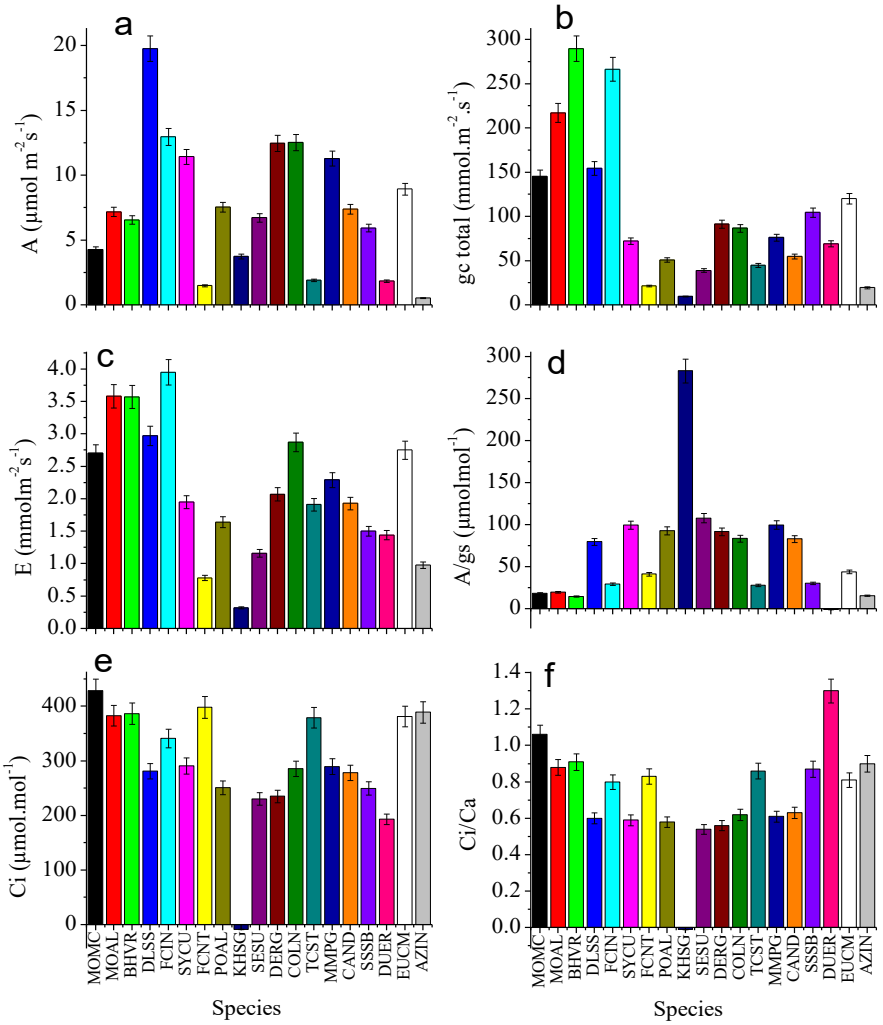

Figure 1. *Photosynthetic variables of tested 19 trees under ambient air conditions. a) A: photosynthetic rate, b) gs: total stomatal conductance, c) E: transpiration rate, d) A/gs: intrinsic water-use efficiency, e) Ci: intrinsic CO_2 concentration, f) Ci/Ca ratio: intrinsic CO_2 to ambient CO_2. Vertical bars represent standard errors. Species abbreviations: MOMC= Morus macroura, MOAL= Morus alba, BHVR= Bauhinia variegata, DLSS= Dalbergia sissoo, FCIN= Ficus infectoria, SYCU= Syzygium cumin, FCNT= Ficus nitida, POAL= Populus alba, KHSG= Khaya senegalensis, SESU= Senna surattense, DERG= Delonix regia, COLN= Conocarpus lancifolius, TCST= Tecoma Stans, MMPG= Mimosa pigra, CAND= Cassia nodosa, SSSB= Sesbania sesban, DUER= Duranta erecta, EUCM= Eucalyptus camaldulensis, AZIN= Azadirachta indica*

A/Ci response curves

The A/Ci response curves (*Fig. 2*) show the interaction between the different concentrations of intercellular CO_2 (C_i) and the net photosynthesis of the tree species. The best relationship between A and C_i was linear (except for *M. macroura*, polynomial fitting). The adjusted R square (R^2) was very high (> 0.75) for *F. infectoria*, *Populus alba*, *Senna surattense*, *D. regia*, *Sesbania sesban*, and *E. camaldulensis*. On the contrary, the interaction between A and Ci was weak in the following species ($R^2 < 0.5$): *F. nitida*, *K. senegalensis*, *Mimosa pigra*, and *A. indica*.

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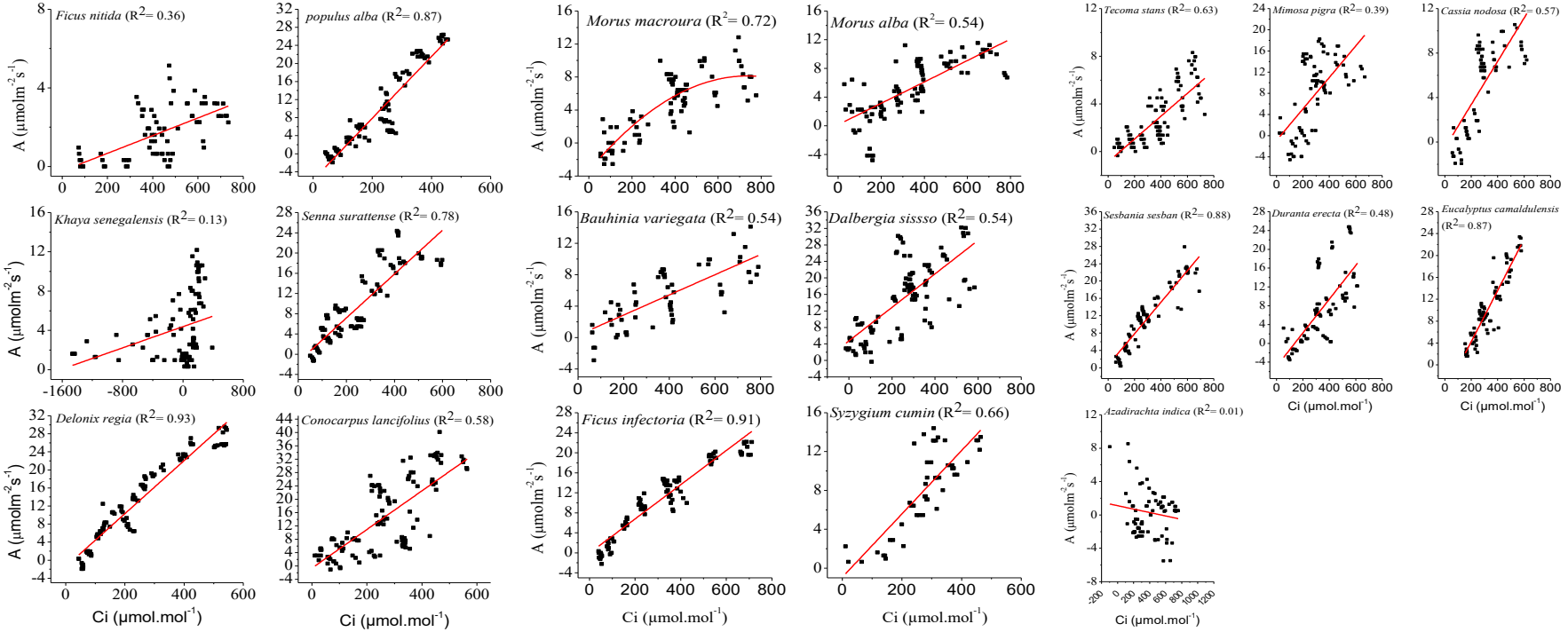

Figure 2. *A/Ci curves for the studied 19 trees. The red lines represent fitting polynomial or linear regression lines. The correlation between photosynthetic rate and Ci of the species is indicated by the adjusted R^2. The name of each species is shown above its relevant panel*

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With increasing CO_2 concentration, the photosynthetic rates of the selected tree species slightly increased, but few species reflected a remarkable increase compared to the others and reached their maximum A values at 800 ppm CO_2 concentration. These species were in the following order: *C. lancifolius*, *D. regia*, *P. alba*, *D. sissoo*, *F. infectoria*, and *S. surattense* (*Fig. 3a*). Most of the tree species had lower transpiration rates (E) with increasing CO_2 concentrations above the ambient level (430 ppm), except for the following species that had slightly higher E values than those at the ambient CO_2 concentrations: *F. infectoria, C. lancifolius, E. camaldulensis, B. variegata*, and *D. sissoo. K. senegalensis* had the lowest E values with increasing CO_2 concentrations (*Fig. 3b*).

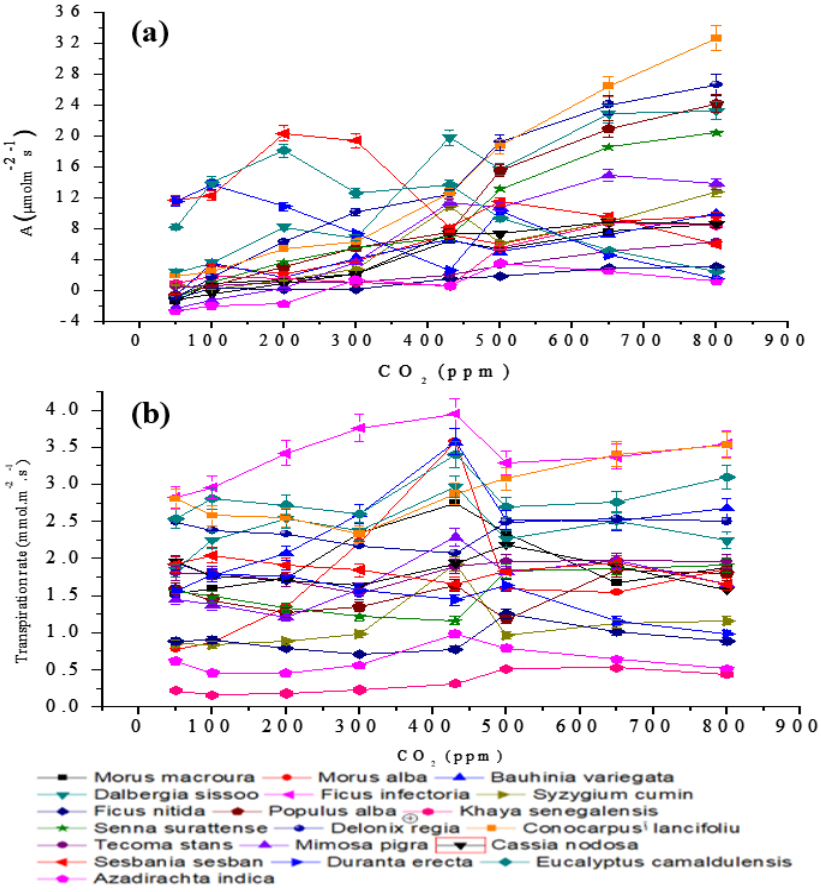

Figure 3. *Variations in photosynthetic rate (a) and transpiration rate (b) of the studied tree species with increasing CO_2 concentrations from 50 to 800 ppm. Data are presented as mean ± SE*

By increasing the CO_2 concentration from 50 to 800 ppm, *D. sissoo* and *Morus alba* were the most responsive species based on their gs values (*Fig. 4a*). In contrast, most tree species did not respond positively to increasing CO_2, and stomatal conductance was mostly stable. In contrast, *Populus alba* had the lowest gs values at different concentrations of CO_2. With increasing CO_2 concentrations from 50 to 800 ppm, the intrinsic CO_2 concentrations (C_i) of the leaves of most tree species increased, except for *D. erecta, E. camaldulensis, A. indica,* and *S. sesban,* which had high C_i concentrations below 430 ppm CO_2 (*Fig. 4b*).

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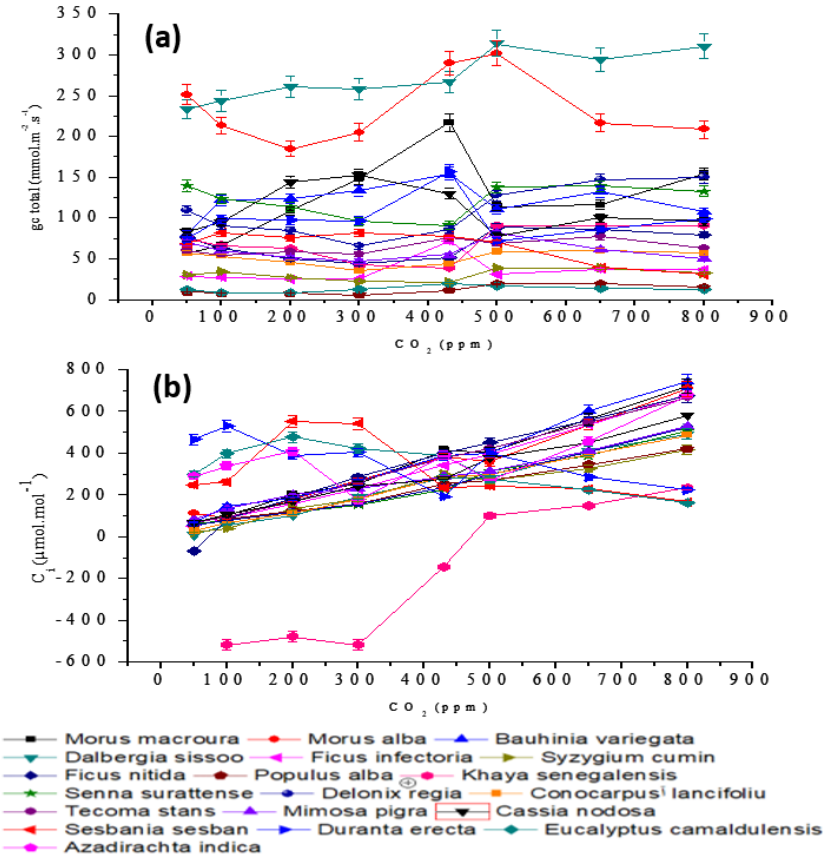

Figure 4. *Variations in a) total stomatal conductance (gs total) and b) intercellular CO_2 (Ci) in the studied tree species under increasing CO_2 concentrations from 50 to 800 ppm. Data are presented as mean ± SE*

The water-use efficiency (A/gs) of the studied tree species steadily increased with increasing CO_2 concentration, with the exception of this behavior (*Fig. 5*). *E. camaaldulesis*, *D. erecta,* and *S. sesban* had the lowest A/gs (WUE), considering their low variation from other species.

Rubisco activity, utilized triose phosphate (TUP) and electron transport chain

The activity of ribulose 1,5 biphosphate carboxylase (Rubisco) showed significant differences among the 19 tested tree species (*Table 2*). Maximum activity of Rubisco was recorded in *P. alba*, *D. erecta*, *D. regia, S. surattensis*, *S. sesban*, and *F. infectoria* ranging from 43.5 to 45.6 µmol CO_2 m^{-2} s^{-1} by increasing CO_2 levels to 800 ppm. In contrast, Rubisco activity was the lowest in *F. nitida.* and *A. indica,* reaching its minimum activity of 0.27 µmol CO_2 m^{-2} s^{-1} in *K. senegalensis,* reaching a same condition.

At elevated CO_2 levels, the utilization of triose phosphate (UTP) was high in *P. alba*, *D. regia, S. sesban, E. camaldulensis*, and *S. surattensis.* However, utilization of triose phosphate was very low in *A. indica* (*Table 2*). Most species such as *B. variegata, C. nodsa, C. lancifolius, D. sissoo*, *D. erecta*, *F. infectoria, F. nitida*, *M. alba*, *M. Pigra* and *M. macroura* var. *alba* had an intermediate capacity for triose phosphate utilization, which matched the low activity of Rubisco (*Table 2*).

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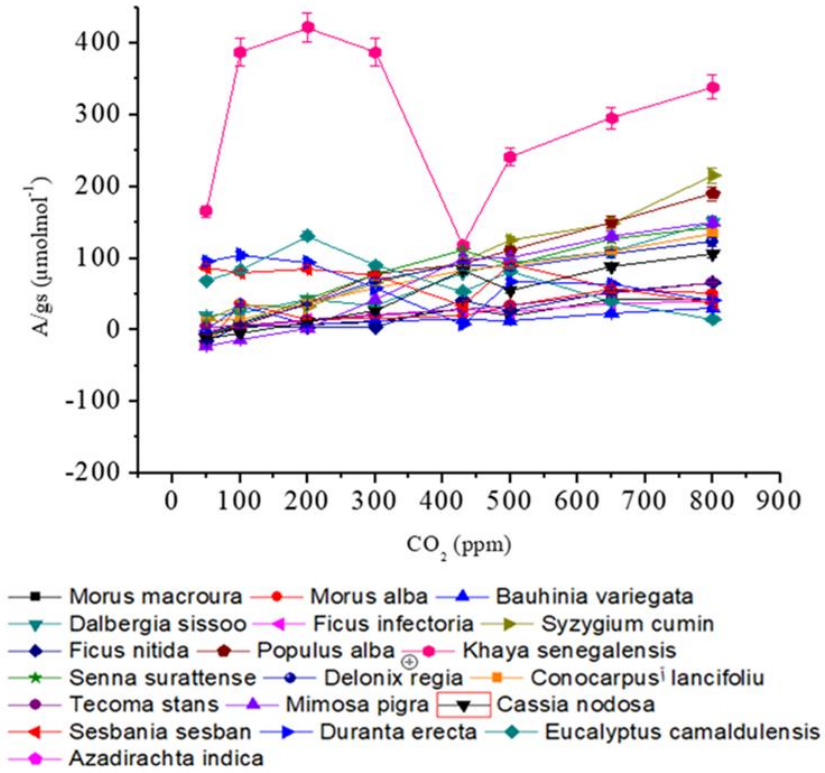

Figure 5. *Water use efficiency (A/gs) of the studied tree species under increasing CO_2 concentrations from 50 to 800 ppm. Data are presented as mean ± SE*

Table 2. *The values of Rubisco activity (Vcmax) (µmol CO_2 m^{-2} s^{-1}), triose phosphate utilization (TPU) (mmol m^{-2} s^{-1}), and PAR-saturated rate electron transport (Jmax) (mol m^{-2} s^{-1}) of the tested tree species under the increase in CO_2 concentration from 50 to 800 ppm*

Tree species	Rubisco activity (V_{cmax})	Triose phosphate utilisation (TPU)	PAR-saturated rate electron transport (J_{max})
Azadirachta indica	3.28	0.0008	0.008
Bauhinia variegata	26	0.0099	0.124
Cassia nodsa	27.2	0.008	0.109
Conocarpus lancifolius	39.1	0.0149	0.174
Dalbergia sissoo	21.7	0.0078	0.0952
Delonix regia	44.8	11.035	131.457
Duranta erecta	45.4	0.0135	0.292
Eucalyptus camaldulensis	8.30	13.411	12.979
Ficus infectoria	43.5	0.0137	0.226
Ficus nitida	7.07	0.0144	0.0274
Khaya senegalensis	0.27	0.027	0.0059
Marus alba	23.9	0.0074	0.111
Mimosa pigra	30.2	0.0105	0.187
Morus nacroura var. alba	20.7	0.0063	0.0858
Populus alba	45.6	31.902	60.940
Senna surattensis	44.5	0.893	33.513
Sesbania sesban	44.2	8.646	118.925
Syzygium cumini	17.9	0.0052	0.0757
Tecoma stans	11.6	0.012	0.0463

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The electron transport rate (J_{max}) was high in species that exhibited high Rubisco activity, reaching its highest rate in *D. regia* (131.457 μmol CO_2 m^{-2} s^{-1}) (*Table 2*). The lowest J_{max} was observed for *A. indica*.

Discussion

Industrial activities and urbanization are among the main contributors to global warming through an increase in carbonaceous emissions. One of the primary causes of climate change is the release of greenhouse gases from various sources, including urbanization, industry, agricultural practices, and transportation, which causes an increase in atmospheric temperature (Kabir et al., 2023). In recent years, there has been a push for nature-based solutions to mitigate these issues, and trees have proven to be an effective solution for removing pollutants from air (Zubair et al., 2022). A growing number of trees in industrial areas is thought to be both ecologically and economically beneficial for carbon sequestration. Sustainable tree management has been shown to raise carbon stocks while producing consistent yields of energy, fiber, and timber.

Trees can absorb CO_2 (store CO_2) and lower its level in atmosphere via photosynthesis (Weissert et al., 2017). Tolia et al. (2019) found that photosynthetic rate alone does not determine growth rates because other factors contribute to the assimilation and partitioning of carbon in plants. Leaf area, duration, and net assimilation rate are important components that affect photosynthetic capability. In many cities, tree-planting programs are extensively used to diminish CO_2 emissions in the air (Auckland Council, 2014). However, it is not scientifically based because of poor knowledge of the contribution of urban vegetation to atmospheric CO_2 sequestration in the studied areas. Therefore, we should improve our understanding of the balance potential of different urban tree species (Peters and McFadden, 2012; Pincetl et al., 2012).The effectiveness of physiological process coordination determines how well a tree species performs under adverse growth conditions (Wright et al., 2005). It is crucial to understand that even minor adjustments to growth rates and water use efficiency (WUE) can have a significant impact on the carbon and water cycles, and ultimately, the pace of climate change (Betts et al., 2004).

According to our study*, F. infectoria* and *D. sissoo* are 20 years old tree, so their photosynthetic rates are higher than those of younger trees. Regarding the size of an individual tree, research shows that the rate of carbon storage steadily increases as the tree becomes older and larger. The factors behind this phenomenon include tree leaves (or needles) providing more leaf area. A larger leaf area allows more atmospheric carbon absorption. Furthermore, the rate of carbon uptake increases even when the total growth efficiency of a tree decreases (Stephenson et al., 2014). According to a recent study, large and old trees do not act simply as senescent carbon reservoirs but actively fix large amounts of carbon compared to smaller trees.

Stomatal conductance (gs), which primarily represents the physical process of CO_2 diffusion, plays a significant role in carbon fixation rate (Tolia et al., 2019). In this study, some trees with a high photosynthetic rate (A) showed elevated stomatal conductance (*Ficus infectoria*). This matches the results of Weissert et al. (2017), who confirmed that more than 50% of the trees used exhibited significant positive relationships between gs and A during different seasons, with maximum values generally reached in winter. Higher transpirational water loss (A/gs) and lower WUE are indicators of higher stomatal conductance. In C_3 plants, increased gs for a certain set of conditions leads to better CO_2

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absorption rates, but worse photosynthetic water-use efficiency (Wullschleger, 1993). Therefore, the optimization of CO_2 uptake by plants with lower gs to minimize water loss is favored (Passioura, 1986; Lawlor and Cornic, 2002). *Delonix regia* showed a balance between high CO_2 fixation and intermediate gs values during the measurements. In other words, *Delonix regia* is economically uses water (low WUE) along with sequestering CO_2 from atomshere. While *F. infectoria* tree showed high A value associated with high gs and E (water loss). Other tree species such as *K. senegalensis* represented the reversal case, having one of the lowest A activities, along with lowest gs, E, but a high WUE. High WUE of *F. infectoria* may be attributed to the isohydric stomatal activity, peaking of gs value throughout the midday, allowing for longer-lasting carbon assimilation and water loss (Franks et al., 2007).

The low water use efficiency of some trees in this study may be attributed to many reasons; one of them is the water requirements of the species itself. To investigate the performance of the studied tree species under different concentrations of CO_2, A/Ci curves were used. Understanding the response curves against the elevation in CO_2 concentrations is important to analyze the role of trees' response in CO_2 sequestration from the atmosphere. According to Leakey et al. (2009), the elevation in atmospheric CO_2 stimulates the uptake of photosynthetic carbon and primary productivity over the long term. Otherwise, higher CO_2 concentration increases the efficiency of nitrogen utilization and reduces water use by leaves.

A few species (C. *lancifolius, D. regia, P. alba, D. sissoo, F. infectoria*, and *S. surattense*) exploited and responded positively to the increase in CO_2 concentrations above the ambient. This reaction reflects the adaptation of those species to the elevation of CO_2 in atmosphere, removing it from atmosphere. Anderson et al. (2012) and Forsman (2015) found that the adaptive reactions to CO_2 in trees may be only plastic phenotypic response or may have an evolutionary cause, clearing that the understanding of these responses will be helpful in the CO_2 managing of future forests. Similarly, Ragula and Chandra (2020) found that *D. regia* had a high ability of CO_2 sequestration.

Tree species transpiration and stomatal curves against CO_2 increment showed lower transpiration along with high water use efficiency in the higher CO_2 sequestering species. This allows the adaptation of plants influencing climate and hydrology (Vicente-Serrano et al., 2022). Stomatal conductance is closely related to A, but it is showed slower magnitude to respond to these variations than photosynthetic responses, that is why a disconnection between A and gs can be occurred, limiting CO_2 uptake and decreasing water use efficiency (Lawson and Vialet-Chabrand, 2019). Like gs, g_m usually declines under elevated CO_2 in the identical mode (Sugiura et al., 2024). Carbon dioxide dependent plant carbon metabolism is predicted to be greatest in arid conditions where reductions in photosynthesis are primarily due to low gs and Ci (Drake et al., 1997). This was seen in some studies such as Wullschleger et al. (2002), and Robredo et al. (2007). Gm was sensitive to change in CO_2, there was a decrease in g_m by elevating CO_2 within 4 min, suggestive the rapid g_m response machinery (Tazoe et al., 2011). Opposing to Tazoe et al. (2011), another study from the same group reported that g_m hardly changed in response to elevated CO_2 in wheat (Tazoe et al., 2009). The contrary responses may be owed to the variances in growth and measurements conditions, affecting g_m reactions to raised CO_2 (Tazoe et al., 2009). Rapid gm responses are most likely caused by changes in CO_2 flow inside cells, such as bicarbonate leakage from chloroplast stroma to cytosol, as well as biochemical reactions including aquaporin and CA down regulation (Tholen and Zhu, 2011). Some Plasma membrane Intrinsic Proteins (PIPs) act as CO_2 channels in

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crops like barley and rice (Hanba et al., 2004; Mori et al., 2014). PIPs aquaporins are controlled by phosphorylation/dephosphorylation, protonation, and perhaps membrane trafficking (Törnroth-Horsefield et al., 2006; Santoni, 2017), which may explain the quick drop in gm. The control of CA, which causes increased amounts of $HCO3^-$ in chloroplasts, is not well described (Lazova et al., 2000). Tholen and Zhu's (2011) reaction diffusion modeling suggests that $HCO3^-$ escapes from chloroplasts to the cytosol, leading to a drop in gm via a decrease in the concentration gradient. So, at low intercellular CO_2 concentrations (C_i), but as C_i grows, net CO_2 assimilation rates (A) peak dramatically (Dusenge et al., 2018).

In the current work, the higher Rubisco activity in *D. regia*, *F. infectoria*, and *P. alba* agreed with their maximum A/C_i photosynthesis rate upon increasing CO_2. High atmospheric CO_2 concentration enhances CO_2 reduction through the Calvin-Benson cycle, and suppressing the photorespiration. This followed by altering electron flow capability parallel to alterations in ATP/NADPH request (Sugiura et al., 2024), owing to the increase of electron transport rates through PSII and PSI (Tan et al., 2021).

Cen and Sage (2016) where they revealed the effect of increasing photorespiration when C_i declined. They used the O_2- and CO_2-insensitive values of *A* to estimate the triose phosphate use rate for their modeled recreations. This improves their ability to sequester CO_2 through high Rubisco activity. The thylakoidal PSII is related to the rate of electron transport, water splitting, and proton gradient across the thylakoid membrane, driving CO_2 through the Calvin cycle (Igamberdiev, 2015). Accordingly, the high rate of electron transport (J_{max}) to produce ATP and NADPH is consistent with Rubisco reaching its V_{max}. The participation of the thylakoidal CA (active carbonic anhydrases) in CO_2 delivery to Rubisco suggests that the chloroplast electron transport not only feeds NADPH and ATP to the Calvin-Benson cycle but also helps to pump CO_2 to Rubisco in the stroma via the CA mechanism (Igamberdiev, 2015). During the dark reaction, Ribulose 1,5 bisphosphate acts as a CO_2 acceptor, producing 3-phosphoglycerate, which in turn is reduced to TPs (triose phosphates). Those trioses which are arise as the main products of this reaction of photosynthesis (McClain and Sharkey, 2019). As C_i increases, photosynthesis is controlled by the ability of Rubisco to fix high CO_2 on Ribulose 1,5 biphosphate followed by the ability to synthesize starch and sucrose from triose phosphates by their reduction by the output of electron transport (ATP and NADPH). However, other species with high to moderate Rubisco activity cannot uses their troises.

The positive response of *D. regia*, *F. infectoria*, and *P. alba* to the increased CO_2 represented in A/C_i curves accompanied with high carbon fixation by maximum Rubisco activity, correlating with their maximum A/C_i photosynthetic rate. These trees which have high CO_2 sequestration may be chosen to be cultivated in the cement factorial areas to filter the air in such areas, preventing CO_2 levels from increasing. Our findigs may find a way to improve the quality of life in some Egyptian cities which has deteriorated by the decline of urban areas and the scarcity of green spaces (Imam, 2006). Green space planning is important for sustainable urban growth (Teal et al., 1998).

Conclusion

We find from this study that the highly active photosynthetic species under elevated CO_2 concentrations (up to 800 ppm) are *C. lancifolius, D. regia, P. alba, D. sissoo,* and *F. infectoria*. From these species, *P. alba and D. regia* showed low stomatal conductance (gc) [18.4 mmol m^{-2} s^{-1} for *P. alba* at 800 ppm CO_2] and high water use efficiency (WUE)

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[190.14 μmol CO_2 $mmol^{-1}$ for *P. alba* at 800 ppm CO_2], along with high photosynthetic rates upon increasing CO_2 concentration. They also exhibited the greatest ability to assimilate CO_2 by Rubisco high carboxylation rate, showing Vcmax of 45.6 and 44.8 μmol m^{-2} s^{-1} at the same conditions. Therefore, we recommend cultivation of *P. alba* and *D. regia* in the greenbelts surrounding Egyptian cement factories and inside them to reduce the high CO_2 levels of pollution caused by the cement industry. It is worth noting that in the present study, the interaction between CO_2 and carbon fixation traits were only considered, while CO_2 interaction with other climate variables were not evaluated here. This is because the main goal of the study was to identify the optimum performed tree species in CO_2 sequestration under ambient and elevated CO_2 concentrations. Additional research is advised to confirm the findings presented here, either through field-scale validation or long-term monitoring in local environmental circumstances.

Competing interests. The authors declare that they have no competing interests.

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