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RESEARCH ARTICLE

CO_2 removal characteristics of a novel type of moss and its potential for urban green roof applications

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Abstract

The feasibility of a novel type of moss (Parkortanso No. 1 synthesized from *Racomitrium japonicum*, Dozy and Molk) to capture CO_2 in urban areas was demonstrated. The effects of light intensity (500, 1000, and 1500 μmol/m^2.s), ambient temperature (10 °C, 25 °C, and 35 °C), age (1-year-old and 3 years old), and leaf color (bright and dark green) on the CO_2 removal caused by the moss concerned were investigated. It was determined that stronger light intensity resulted in higher CO_2 removal by the target moss. The moss showed the best CO_2 capture at 25 °C, while the CO_2-capturing capacities declined when the ambient temperatures were 10 °C and 35 °C. Three years old bright green moss was found to have higher CO_2-capturing capacity than 1 year old. Similarly, bright green moss exhibited the best CO_2 uptake out of the mosses concerned. The highest net CO_2 emission of the moss was − 1.94 ± 0.72 kgCO_2/m^2.year, which was comparable to other moss and plant species. Consequently, the bright green and old Parkortanso No. 1 moss are recommended for a green roof application in terms of CO_2 capture.

Keywords Climate change, CO_2 capture, Green roof, Moss, Urban sustainability

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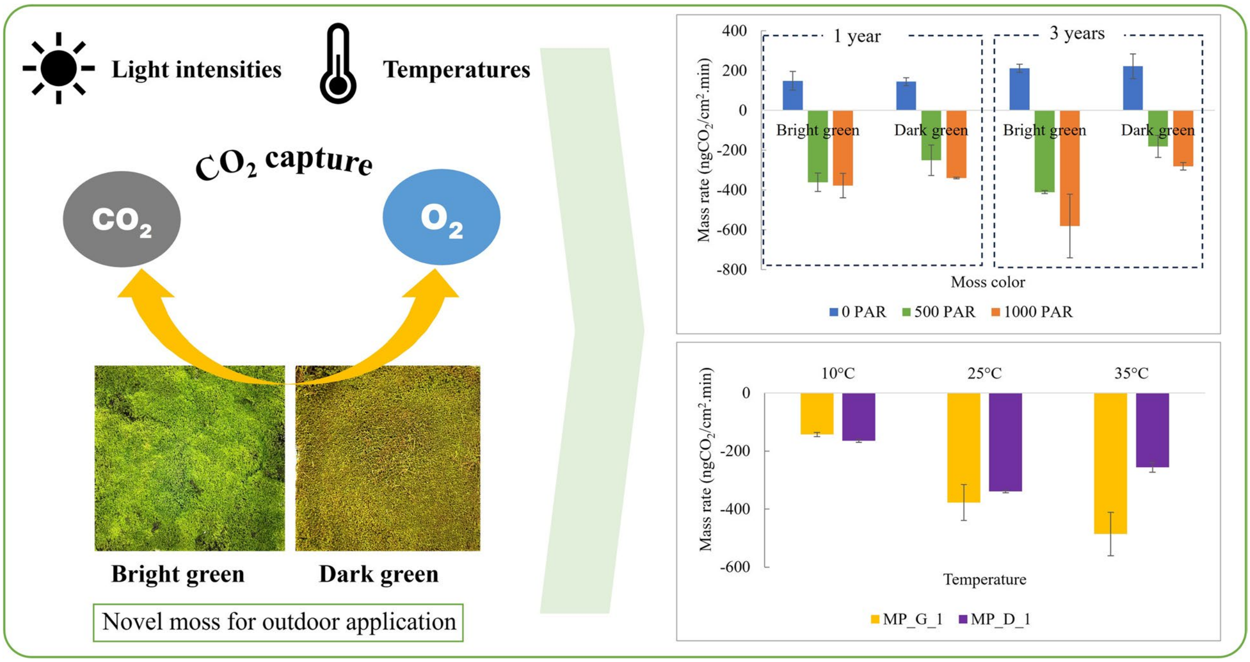
Graphical Abstract



1 Introduction

The heat island effect is an essential issue in urban areas because it causes them to have higher temperatures than outlying areas (Gago et al., 2013; U.S. EPA, 2023). It was reported that the temperature of urban areas in the United States of America was approximately 7% higher than that of rural areas in the daytime and approximately 6% higher than that of rural areas at night (U.S. EPA, 2023). The cooling load in London was found to be 25% higher than the load in rural areas due to the heat island effect (Kolokotroni et al., 2007). Furthermore, the heat island effect was found to cause an increase in temperature of 10 °C in Athens, Greece (Santamouris et al., 2001). Generally, the heat island effect leads to an increase in energy consumption and CO_2 emissions in urban areas, which increases the burden of climate change effects (Gago et al., 2013; U.S. EPA, 2023). To overcome this problem, the use of green roofs has been widely recommended (Gago et al., 2013; Shafique et al., 2018; U.S. EPA, 2023). In addition to reducing temperatures in urban areas, green roofs have many other benefits, including CO_2 and particle capture, stormwater retention and water quality improvement, noise reduction, and habitat loss reduction (Shafique et al., 2018). However, selecting proper vegetation and taking care of roofs throughout various seasons are challenging (Shafique et al., 2018). Thus, investigating the feasibility of various vegetation species for green roofs is necessary with respect to various temperature and light conditions.

Mosses, which are small, nonvascular, flowerless plants, have been found to play an important role in ecosystems, making many positive contributions. In particular, mosses can capture and store up to approximately 6.43 gigaton's worth of carbon on a global scale (Eldridge et al., 2023). Therefore, they significantly contribute to mitigating climate change. In terms of air pollution control, mosses have also been found to capture particulate matter, volatile organic compounds, and heavy metals (Gong et al., 2019; Haynes et al., 2019; Kosior et al., 2018; Tretiach et al., 2011). It was reported that *Plagiomnium cuspidatum*, *Myuroclada maximowiczii*, and *Etodon luridus* could capture particulate matter with sizes of less than 10 μm (PM_{10}) (Gong et al., 2019). *Hypnum cupressiforme* can remove up to 98% of PM_{10} (Tretiach et al., 2011), while *Hylocomium splendens* has been found to capture Cd, Ni, Pb, and Zn in the air (Kosior et al., 2018). It was found that moss turf captured 3.8 times more $PM_{2.5}$ than tree leaves (Haynes et al., 2019). When an adequate amount of moss is used, *Plagiomnium cuspidatum* and *Myuroclada maximowiczii* can reduce 50% of volatile organic compounds (VOCs) in the air (Gong et al., 2019). Furthermore, mosses can tolerate harsh conditions (e.g., extreme cold, extreme heat, and drought) (Drake et al., 2018; Heim et al., 2014; K. et al., 2018). For example, it was reported that 70% of Alaska's interior was covered by moss (Yuan et al., 2014). Accordingly, moss is a good candidate for green roof applications. However, only a few studies on the effects of moss on green roofs could be found in various publications, such as the effect of moss green roofs on heat reduction (Heim et al., 2014; K. et al., 2018), the effect of moss green roofs on biodiversity (Drake et al., 2018; Marttinen et al., 2020; Van Dijck et al., 2023), the water storage capacity of moss green roofs (Bengtsson, 2005), and the effects of weather conditions on various moss species (Nagase et al., 2023). Additionally, a lack of research on the effect of moss green roofs on CO_2 capture with respect to light intensity and environmental temperature has been reported.

Consequently, this study was conducted to investigate the feasibility of using a new type of moss (i.e., Parkortanso No. 1 synthesized from *Racomitrium japonicum,* Dozy and Molk) for green roof application in terms of its capability to capture CO_2. This new moss was synthesized for CO_2 capture and outdoor applications. Its CO_2 capture ability was investigated with respect to various light intensities and temperatures.

2 Materials and methods

2.1 Moss specifications

A new type of moss, referred to herein as MP, invented by Parkor Bio & Green Co. Ltd. in the Republic of Korea, was used in this study to investigate its potential application for green roofs in the Republic of Korea. Its commercial name is Parkortanso No. 1, which was synthesized from *Racomitrium japonicum* (Dozy and Molk). The effects of various conditions on the CO_2 capture capacity of Parkortanso No. 1 moss were investigated. Parkortanso No. 1 moss ages were approximately 1 year old and 3 years old. In addition, two other mosses were collected from nature in the Republic of Korea: *Brachythecium buchananii* (Hook.) A. Jaeger (i.e., silk moss) and *Thuidium kanedae* Sakurai (i.e., feather moss) were compared with artificial moss in terms of CO_2 capture capability and were coded as MS and MF, respectively. The two mosses were selected because they are widely distributed in the Republic of Korea (Bum et al., 2021; Kim et al., 2020a, b). The study subjects and moss specifications are shown in Table 1. Because MS and MF were collected from nature, it was difficult to determine their exact ages.

2.2 Experimental methods

The capacity of each moss sample to capture CO_2 was investigated and compared with respect to five parameters: light intensity, environmental temperature, moss age, moss leaf color, and moss species. To maintain the same conditions for all experiments, a 25-L Tedlar bag (SKC Ltd., Dorset, United Kingdom) was used to create an environmental chamber that was placed within an isolated box to ensure a consistent temperature. Since the seasonal average surface air temperature in the Republic of Korea recently varied from approximately 5 °C in winter to 25 °C in summer (Choi et al., 2018), the target temperatures for this study were 10 °C, 25 °C, and 35 °C. Ice packs, heaters, and ventilation fans were employed to regulate and maintain the temperature. Each moss sample was cut into a rectangular shape with dimensions of 30 cm × 30 cm.

For monitoring purposes, two CO_2 sensors (MB-350WDO2, ELT Sensor, Gyeonggido, Republic of Korea) were utilized for a range of 0–10,000 ppm and 3% reading accuracy. These sensors were employed to measure CO_2 levels both inside and outside the chamber and to prevent leakage. The laboratory's air, which had a relative humidity of 50 ± 5% at 25 °C and a CO_2 concentration of 550 ± 50 ppm, was introduced into the chamber to initiate testing. The aim of this study was to investigate the CO_2 capture capability of moss in its most comfortable conditions, avoiding any stress caused by the lack of elements found in natural air. Consequently, natural air containing CO_2 was used in our experiments instead of artificial standard gas. The building's ventilation system was

Table 1 Specifications of the moss samples used in the current study

Code	Moss species	Age (years)	Leaf color
MP_G_1	Modified *Racomitrium japonicum,* Dozy and Molk	1	Bright green
MP_G_3		3	Bright green
MP_D_1		1	Dark green
MP_D_3		3	Dark green
MS	*Brachythecium buchananii* (Hook.) A. Jaeger	–	Bright green
MF	*Thuidium kanedae* Sakurai	–	Bright green

employed, and the number of people in the laboratory was regulated to control temperature, humidity, and CO_2 conditions. Throughout the experimental period, only one person entered the laboratory to conduct the experiment and log the data. Before commencing each experiment, air was continuously introduced into the chamber, and its CO_2 concentrations were consistently monitored by the CO_2 sensor inside the chamber. This was done to ensure that the initial CO_2 concentration was within the range of 550 ± 50 ppm in each experiment. Each experiment lasted for two hours. The data logging interval of the sensor was 1 s. Initial and final CO_2 concentrations were utilized to compute the amount of CO_2 emission or reduction, which was dependent on light intensity. The rate of CO_2 emission or reduction was calculated using Eq. (1) at 25 °C and 1 atm. The net CO_2 emission ($kgCO_2/m^2$.year), which demonstrates the total CO_2 intake or uptake of moss in a year, was calculated using Eq. (2),

$$CO_2 \text{ mass} = \frac{C_{CO2} \times M \times V}{24.45 \times A \times t} \times 10^3 \quad (1)$$

where CO_2 mass ($ngCO_2/cm^2$.min) is the emission or reduction rate of CO_2, C_{CO2} (ppm) is the difference of CO_2 concentration after t min, V (L) is the volume of air in the chamber, A (cm^2) is the area of moss in the chamber, t (min) is the selected duration to compare, M (g/mol) is the molecular weight of CO_2, 24.45 L/mol is the air volume of 1 mol air at 25 °C and 1 atm,

$$\text{Net } CO_2 \text{ emissions} = CO_2 \text{ mass}_1 - CO_2 \text{ mass}_2 \quad (2)$$

where CO_2 mass_1 ($kgCO_2/m^2$.year) is the CO_2 reduction rate when PAR > 0 and CO_2 mass_2 ($kgCO_2/m^2$.year) is the CO_2 emission rate when PAR = 0.

Light intensity was determined using photosynthetically active radiation (PAR, μmol/m^2.s) through a PAR sensor (748205–02, Hawthorne Hydroponics LLC, Vancouver, Canada). As the average PAR in the Republic of Korea fluctuates with seasons, ranging from around 450 μmol/m^2.s in winter to 1300 μmol/m^2.s in summer (Choi et al., 2021), this study considered target PAR values of 0 μmol/m^2.s, 500 μmol/m^2.s, 1000 μmol/m^2.s, and 1500 μmol/m^2.s. LED lights (1325 lumens, Koninklijke Philips N.V., Amsterdam, Netherlands) were used to produce PAR for the experiment. Each experiment was repeated three times. The experimental setup is presented in Fig. 1, and an illustration of the moss sample is provided in Fig. 2.

All data charts were presented using Microsoft Office Excel (Version 2307, Microsoft Cooperation, Redmond, Washington, USA). Statistical analysis was conducted using MATLAB software (Version 9.10.0.1684407, MathWorks, Inc., Natick, USA).

3 Results and discussion

3.1 Influence of moss ages and leaf colors on CO_2 removal characteristics of synthesized *Racomitrium japonicum* Dozy and Molk mosses

To compare the CO_2 emission and uptake associated with different moss ages and leaf colors, the t value was set to 30 min in Eq. (1). The area of the moss sample was 900 cm^2, and the volume of air in the chamber was 25 L. The experiment was conducted at 25 °C. PAR values were 0, 500, and 1000 μmol/m^2.s. When PAR was 0 μmol/m^2.s, the mass rate was positive, indicating the moss' CO_2 emission. When PARs were 500 and 1,000 μmol/m^2.s, the mass rate was negative, indicating the moss' rate of CO_2

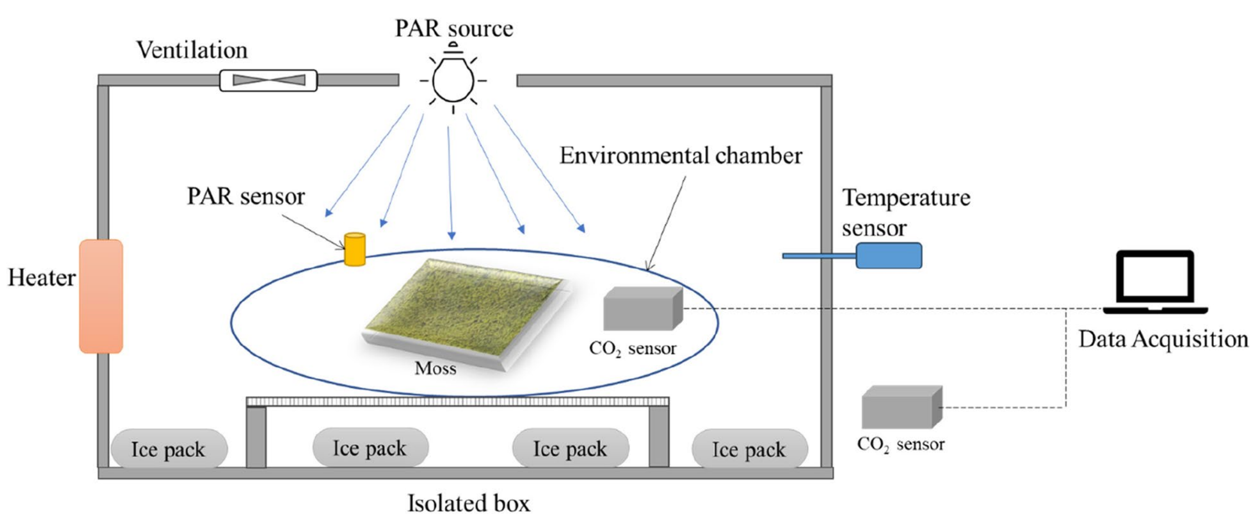


Fig. 1 Experimental setup for investigating the moss samples' capability to capture CO_2

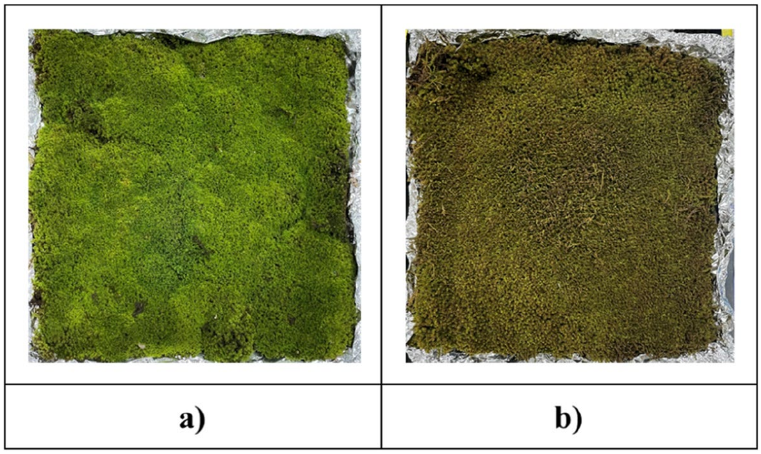


Fig. 2 Example of MP moss samples used in this study: **a** bright green and **b** dark green

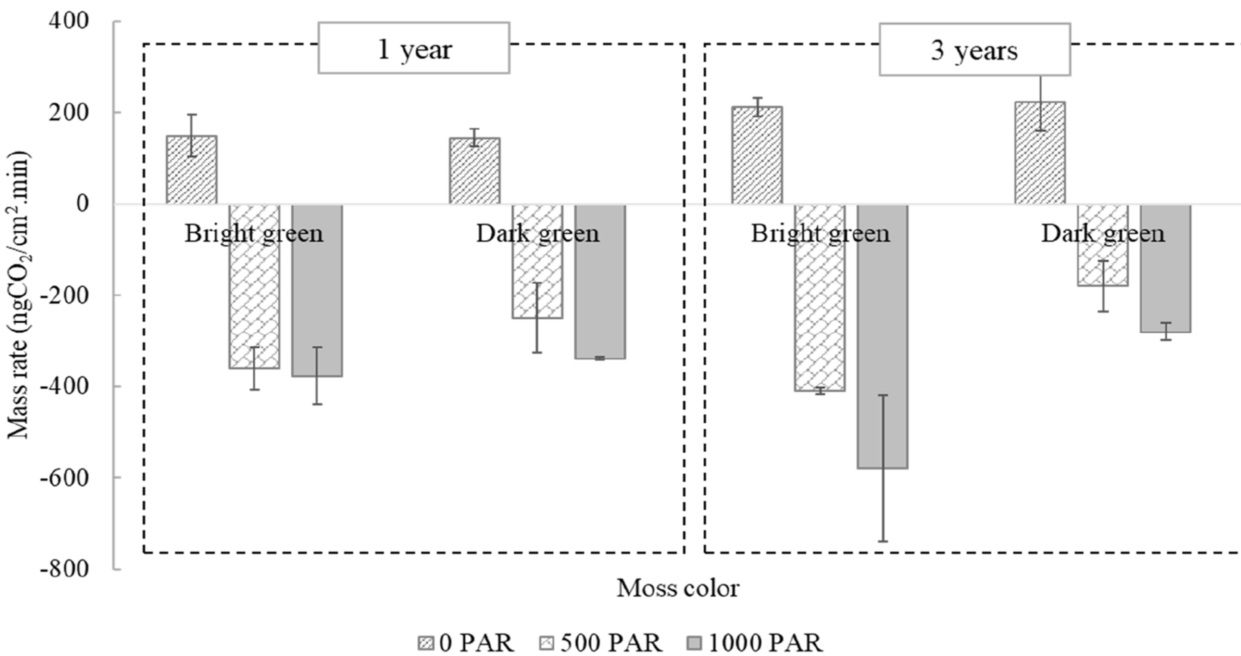


Fig. 3 CO_2 mass emission and reduction rates of synthesized *Racomitrium japonicum* Dozy and Molk moss with respect to various moss ages and leaf colors

capture by the moss. The experimental results are presented in Fig. 3.

As shown in Fig. 3, the older moss demonstrated stronger CO_2 emission and uptake than the younger moss across all conditions. However, the older dark green moss revealed stronger CO_2 emission but weaker CO_2 capture than that of the younger moss. Therefore, when the CO_2 capture rate is taken into account by synthesized *Racomitrium japonicum* Dozy and Molk moss, younger moss is recommended if the leaves are dark green, and older moss should be used if the leaves are bright green. In terms of leaf colors, the bright green and dark green samples showed similar CO_2 mass emission rates at a PAR of 0 (μmol/m^2.s) (Fig. 3). The *t*-test analysis (95% confidence interval) confirmed that there was no significant difference between the mean values of CO_2 mass emission rates of the bright-green and dark-green samples (i.e., p values > 0.7). In contrast, when mosses were exposed to light (i.e., PAR = 500 and 1000 μmol/m^2.s), the CO_2 mass capture rates were significantly different across the two leaf colors. The bright green samples revealed much higher CO_2 capture rates than the dark green samples (Fig. 3). Particularly, 3-year-old dark green moss had a lower CO_2 capture rate than its CO_2 emission rate at 500 PAR. The effect of moss leaf color on CO_2 emission or capture was also identified in another study (Nakatsubo et al., 2023). It was reported that mosses such as *Calliergon richardsonii* (Mitt.) Kindb. and *Tomenthypnum nitens* (Hedw.) Loeske with green leaves showed a stronger CO_2 exchange rate than those with brown leaves (Nakatsubo et al., 2023). Therefore, this suggests that bright green moss be used for green roofs if CO_2 capture purposes are taken into account when synthesized *Racomitrium japonicum* Dozy and Molk mosses are applied.

3.2 Influence of PAR on CO_2 removal characteristics of synthesized *Racomitrium japonicum* Dozy and Molk mosses

To compare CO_2 capture with respect to various PARs, CO_2 mass was also estimated based on Eq. (1) with $t=30$ min and $A=900$ cm^2. The experiment was conducted at 25 °C. PAR values varied from 0, 500, 1000, and 1500 μmol/m^2.s. The experimental results are shown in Fig. 4.

As shown in Fig. 4, a stronger light intensity led to stronger CO_2 capture rates via photosynthesis. A similar trend was found in other mosses (Nakatsubo et al., 2023). The CO_2 capture rate of *Calliergon richardsonii* (Mitt.) Kindb. increased from approximately 0.5 mgCO_2/g.h at 200 μmol/m^2.s of PAR to approximately 0.7 mgCO_2/g.h at 1000 μmol/m^2.s of PAR (Nakatsubo et al., 2023). *Tomenthypnum nitens* (Hedw.) Loeske was found to be approximately 0.3 mgCO_2/g.h at 200 μmol/m^2.s of PAR to approximately 0.4 mgCO_2/g.h at 1000 μmol/m^2.s of PAR (Nakatsubo et al., 2023). It is also worth noting that the increase in CO_2 sink amount of these mosses with respect to the increase of PAR (max 1.4-fold) was lower than that of modified *Racomitrium japonicum* Dozy and Molk (max 1.6-fold) in this current study. Thus, the modified *Racomitrium japonicum* Dozy and Molk showed a relatively good capability to capture CO_2.

3.3 Influence of ambient temperatures on CO_2 removal characteristics of synthesized *Racomitrium japonicum* Dozy and Molk mosses

To investigate the effect of temperature on the CO_2 capture rates of mosses, bright green and dark green mosses aged one year old were used. PAR was set at 0 and 1000 μmol/m^2.s to compare the emissions and uptakes of CO_2 in order to demonstrate CO_2-capture ability. CO_2 mass rates were also calculated based on Eq. (1) with $t=30$ min and $A=900$ cm^2. The experimental results are depicted in Fig. 5.

As shown in Fig. 5, ambient temperature denotes a significant effect on the CO_2 exchange of mosses. The higher the temperature, the greater the CO_2 emission was found when the temperature increased from 10 to 35 °C in both bright green and dark green mosses. This revealed a similar pattern to other mosses in nature (Nakatsubo et al., 2023). The CO_2 emission of *Calliergon richardsonii* (Mitt.) Kindb. moss increased approximately 3-fold when the temperature increased from 5 to 25 °C, and that of *Tomenthypnum nitens* (Hedw.) Loeske moss increased approximately 2-fold (Nakatsubo et al., 2023). In terms of CO_2 capture in the presence of light, the MP_D_1 sample (dark green moss)

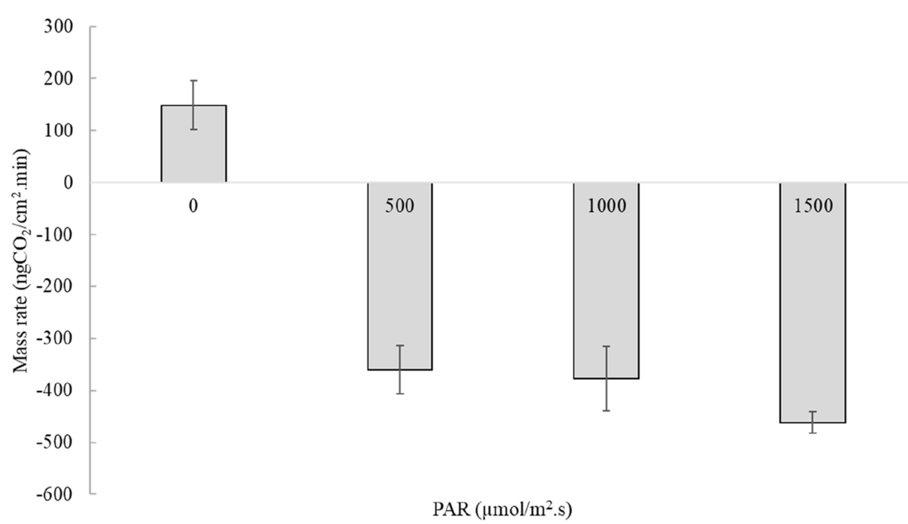


Fig. 4 CO_2 emission and reduction rates of MP_G_1 with respect to different PARs at 25 °C

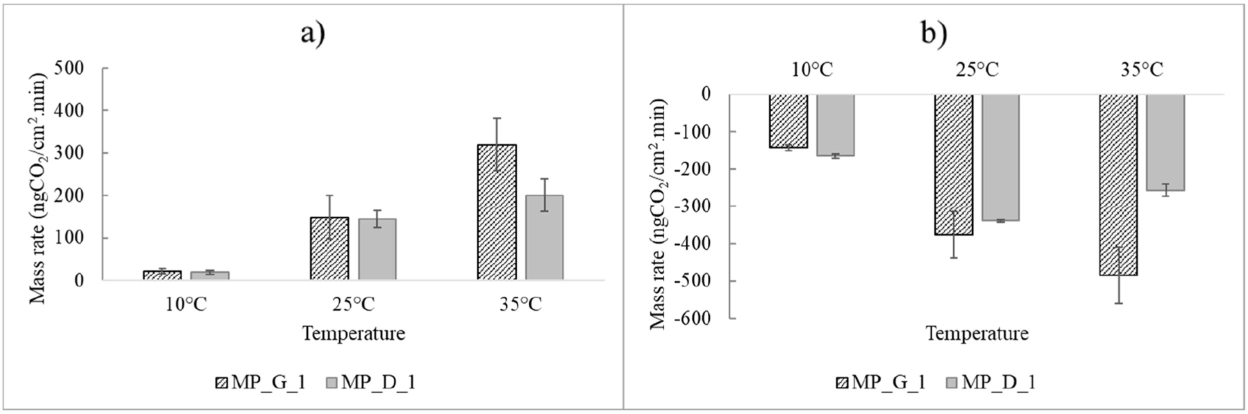


Fig. 5 CO_2 emission (**a**) and reduction (**b**) of various moss samples at 10 °C, 25 °C, and 35 °C

showed greater CO_2 reduction at 25 °C than at 10 °C. However, its CO_2 reduction decreased when the temperature increased from 25 to 35 °C. This pattern was similar to that found in another study. The *Calliergon richardsonii* (Mitt.) Kindb. and *Tomenthypnum nitens* (Hedw.) Loeske mosses at 25 °C were found to have an approximately 1.3-fold lower CO_2-capture ability than those at 10 °C, but they have similar CO_2-capture ability to those at 5 °C (Nakatsubo et al., 2023). In other words, the *Calliergon richardsonii* (Mitt.) Kindb. and *Tomenthypnum nitens* (Hedw.) Loeske mosses showed the highest CO_2 capture capacity at around 10 °C, and the CO_2 capture capacity decreased when the temperatures were higher or lower than 10 °C. In contrast, the CO_2 capture capacity of the MP_G_1 (bright green moss) sample was proportional to temperature variation. A higher temperature led to a higher CO_2 capture capacity. Therefore, the current Parkortanso No. 1 can well capture CO_2 at higher temperatures than other natural mosses. This difference might be due to the mosses' characteristics. Moss is generally found in shade and cool areas; thus, higher temperatures might affect moss activity. In contrast, the current Parkortanso No. 1 moss was synthesized to be applied outdoors and to capture CO_2. Indeed, this moss showed high potential for a green roof. However, only the bright green Parkortanso No. 1 moss demonstrated this good capability. The CO_2 capture capacity of MP_D_1 (dark green moss) increased when the ambient temperature increased from 10 to 25 °C, but it decreased when the temperature increased from 25 to 35 °C. Accordingly, when synthesized *Racomitrium japonicum* Dozy and Molk moss is applied to a green roof to capture CO_2, bright moss is recommended for both cool and hot environments. In contrast, dark moss should not be used to capture CO_2 in high-temperature environments such as the summer season.

3.4 Comparison of the CO_2 removal capacities of synthesized *Racomitrium japonicum* Dozy and Molk mosses with other natural mosses

Three moss species (Table 1) were compared in terms of CO_2 emission and reduction rates at the same light intensity (i.e., 0 and 500 μmol/m^2.s) and temperature (i.e., 25 °C) (Fig. 6).

As shown in Fig. 6, the MP_G_3 sample demonstrated the highest CO_2 reduction rate among the target mosses in this study. To confirm the CO_2 capture capability of different mosses, net CO_2 emission per m^2 was calculated for a year based on Eq. (2). Since PAR = 0 is representative of nighttime and PAR = 500, 1000, or 1500 is representative of daytime, the total daytime and nighttime for a year was assumed to be equal when evaluating net CO_2 emission. The results are shown in Table 2. The negative net CO_2 emission value indicates CO_2 sink or CO_2 capture. A positive value indicates CO_2 production or CO_2 exhaust.

As shown in Table 2, MP_G_3 sample had the best net CO_2 emissions. The net CO_2 emissions of the MP_D_3 sample was + 0.22 kgCO_2/m^2.year, indicating that it releases more CO_2 rather than capturing CO_2. In addition, a higher ambient temperature could reduce the CO_2 sink of the novel moss. Thus, synthesized *Racomitrium japonicum* Dozy and Molk moss was the most optimal moss for CO_2 capture out of the mosses concerned in this study. However, to ensure the ability to capture CO_2, the bright green moss should be used when the temperature is high and the light intensity is weak because the dark green moss demonstrated CO_2 emissions higher than its CO_2 uptakes when the light intensity was weak. The

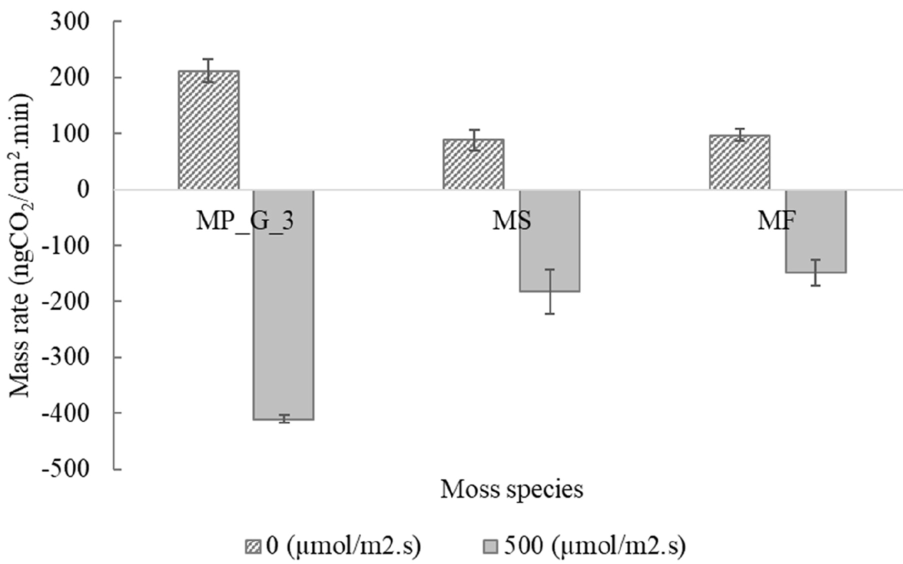


Fig. 6 CO_2 emission and reduction rates associated with various moss species at 25 °C

Table 2 Net CO_2 emissions (kgCO_2/m^2.year) of various moss samples under different conditions

PAR	500 (μmol/m^2.s)		1000(μmol/m^2.s)			1500(μmol/m^2.s)
Temp	10 °C	25 °C	10 °C	25 °C	35 °C	25 °C
MP_G_1	−0.58 ± 0.12	−1.11 ± 0.17	−0.68 ± 0.01	−1.25 ± 0.14	−0.87 ± 0.09	−1.64 ± 0.21
MP_G_3	−0.97 ± 0.12	−1.04 ± 0.09	−0.94 ± 0.04	−1.94 ± 0.72		
MP_D_1	−0.54 ± 0.03	−0.64 ± 0.08	−0.74 ± 0.05	−1.03 ± 0.09	−0.29 ± 0.01	
MP_D_3	−0.48 ± 0.10	0.22 ± 0.1	−0.66 ± 0.02	−0.57 ± 0.37		
MS		−0.42 ± 0.12				
MF		−0.24 ± 0.12				

best CO_2 sink of the synthesized *Racomitrium japonicum* Dozy and Molk moss was measured at 1.94 ± 0.72 kgCO_2/m^2.year. This value was comparable to that of other vegetation. *Polytrichum juniperinum* moss in interior Alaska was found to capture approximately 1.46 kgCO_2/m^2.year (Kim et al., 2014). The CO_2 sink caused by moss carpets consisting of *Scorpidium scorpioide*s and *Drepanocladus trifarius* at Zackenberg in Greenland was estimated to be approximately 0.005 kgCO_2/m^2.year (Riis et al., 2016). *Hylocomium splendens* moss in the Trento and Vicenza provinces in Italy was found to have a CO_2 capture rate of 0.24 ~ 0.63 kgCO_2/m^2.year (Gerdol et al., 2002). *Calliergon richardsonii* (Mitt.) Kindb. and *Tomenthypnum nitens* (Hedw.) Loeske mosses had approximately 0.55 ~ 0.73 kgCO_2/m^2.year of CO_2 sink (Nakatsubo et al., 2023). Hyyti¨al¨a, a forest in southern Finland that is mainly composed of Scots pine trees, was found to have an average CO_2 sink of approximately 0.73 kgCO_2/m^2.year (Lagergren et al., 2008). Sorø forest in eastern Denmark, with mainly beech trees, showed an average CO_2 sink of 0.72 kgCO_2/m^2.year (Lagergren et al., 2008). The CO_2 sink obtained by 18 monitoring sites for Canadian forests with pine trees varied from 0.35 to 2.3 kgCO_2/m^2.year (Zha et al., 2013). It was reported that the Kalevansuo and Lettosuo boreal forests in Finland could capture approximately 3.3 ~ 3.7 kgCO_2/m^2.year (Kasimir et al., 2021).

The CO_2 capture and storage ability can be demonstrated through the carbon fraction in vegetation tissue. The modified *Racomitrium japonicum* Dozy and Molk in the current study had approximately 44.6% carbon in its tissue. This was comparable to, and even higher than, some other mosses. *Haplocladium microphyllum* (Hedw.) Broth, *Haplocladium angustifolium* (Hampe et C. Muell.) Broth, *Brachythecium salebrosum* (Web. et Mohr.) B. S. G., and *Eurohypnum leptothallum* (C. Muell.) Ando. mosses were reported to have tissues with 39.5 ~ 45.66% of carbon depending on location (Liu et al., 2010). *Scorpidium scorpioide*s was reported to be made up of 41.30% ± 0.62% carbon in its tissues (Riis et al., 2016). The carbon percentages in *Drepanocladus trifarius* and *Sarmentypnum tundrae* were 41.62% ± 0.78% and 41.54% ± 1.07%, respectively (Riis et al., 2016). Carbon percentages were comparable to those of trees. It was reported that the mean carbon fractions of stem wood of tropical angiosperm and conifer trees were 47.1% and 49.3%, respectively, while those of subtropical/Mediterranean angiosperm and conifer trees were 48.1% and 50.54%, respectively (Thomas & Martin, 2012). It was also found that mosses helped improve carbon accumulation in poor soil that lacked other kinds of vegetation (Kasimir et al., 2021; Yang et al., 2019). This suggests that the current moss, Parkortanso No. 1, is a good candidate for making green roofs without having to use other trees. It should be noted that bright green moss should be used for better CO_2 capture capacity with respect to variations in environmental temperatures and light intensities. The limitations of this experiment were the lower temperatures (e.g., temperatures ≤ 0 °C). Therefore, further studies should be conducted to investigate the effect of cold conditions on CO_2 capture characteristics of mosses. Moreover, field tests on building roofs should be conducted in future work to demonstrate the influence of real weather conditions by seasons on CO_2 capture characteristics of mosses.

4 Conclusions

A new moss, Parkortanso No. 1 (synthesized from *Racomitrium japonicum*, Dozy and Molk) had its feasibility as a green roof vegetation to capture CO_2 investigated. Various conditions, including ambient temperature, light intensity, leaf color, and age, were compared. A comparison with other natural moss species in the Republic of Korea, including *Brachythecium buchananii* (Hook.) A. Jaeger. and *Thuidium kanedae* Sakurai were carried out in terms of CO_2 capture capability. The results show that the new moss had the highest CO_2 sink capacity among the mosses of concern. The best CO_2 sink level achieved for this novel moss was found to be comparable to other mosses and plants. The experimental results show that old and bright green Parkortanso No. 1 could be used as a green roof to capture CO_2 in urban areas. Additional studies involving field trials and other environmental conditions should be conducted in the future.

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Authors' contributions
Ye-Bin Seo and Seungjae Kim: experiment, writing—original draft, software, data collection, visualization. Da-Hyun Baek and Kweon Jung: formal analysis, data curation, funding acquisition. Trieu-Vuong Dinh and Jo-Chun Kim: conceptualization, writing—review and editing, supervision, project administration. All authors read and approved the final manuscript.

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Availability of data and materials
All data generated or analyzed during this study are included in this published article.

Declarations

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

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