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RESEARCH

Bark, soil and lichens are effective indicators of dust from limestone industries in Thailand

Chaiwat Boonpeng · Pitakchai Fuangkeaw · Kansri Boonpragob

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Abstract Cement production, quarrying and stone crushing are major emission sources of alkaline dust that can affect human health and vegetation. The main objectives of this study were to evaluate the potential of using bark pH, soil pH and lichen community for indicating alkaline dust pollution. Twelve polluted sites were in a limestone industrial area. Bark pH and the lichen community were observed on *Alstonia scholaris* trees, and soil pH was obtained from topsoil samples. The bark pH at all polluted sites was significantly higher (5.5 to 7.3) than that at the unpolluted site (4.3). Among the polluted sites, the highest bark pH value was observed at the nearest site to the center of the industrial area, while the lowest value was discovered at the farthest site. Bark pH showed a strongly negative correlation with the distance from the center. Soil pH at the unpolluted site (6.3) was also significantly lower than that at the polluted sites (7.6 to 8.1), except at the farthest site (6.5). The soil pH also tended to increase closer to the center. Seven lichen species were observed on the trunks of investigated trees in all polluted sites and were observed only at sites more than 4.7 km away from the center, where bark pH ranged from 5.5 to 6.3. The extent of dust impact on vegetation seemed to be within 6–7 km from the center. The results of this study confirm the potential of the bark pH of *A. scholaris*, soil pH and lichen community as long-term indicators of alkaline dust pollution.

Keywords Air pollution · *Alstonia scholaris* · Cement plant · Limestone quarry · Particulate matter

Introduction

Dust consists of solid matter in which the particle is small enough to be raised and carried by wind (Farmer, 1993). The sizes range from below 1 µm to more than 100 µm. Dust is emitted by several activities such as combustion and noncombustion processes of industrial plants, mining, traffic vehicles, agricultural activities, construction, volcanic eruptions, wildfire, wind-blown dust and sea aerosol (Rienda & Alves, 2021; WHO, 2013). Among these, cement production, quarries and stone crushing plants are the major emission sources

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C. Boonpeng (✉)
Department of Biology, Faculty of Science, Ramkhamhaeng University, Hua Mark, Bang Kapi, Bangkok 10240, Thailand
e-mail: chaiwat.b@ru.ac.th

C. Boonpeng · P. Fuangkeaw · K. Boonpragob
Lichen Research Unit, Department of Biology, Faculty of Science, Ramkhamhaeng University, Hua Mark, Bang Kapi, Bangkok 10240, Thailand

(Adeyanju & Okeke, 2019; Bluvshtein et al., 2011). Cement and limestone ($CaCO_3$) quarry dusts are more alkaline because their chemical compositions are mainly Ca, Fe, K, Mg and Si (Branquinho et al., 2008; Chulamanee et al., 2014; Paoli et al., 2014; Świercz, 2006). Exposure to cement dust pollution causes several health effects and can influence flora and fauna (Adeyanju & Okeke, 2019; Thepaksorn et al., 2013). Dust particles with an aerodynamic diameter of 10 µm or less belong to the particulate matter (PM) group that causes serious health effects (WHO, 2013). The International Agency for Research on Cancer (IARC) has classified PM as a Class I carcinogen to humans (Hoek & Raaschou-Nielsen, 2014; Loomis et al., 2014). According to the report of WHO (2013), PM10 (PM with a diameter of 10 µm or less) and PM2.5 (PM with a diameter of 2.5 µm or less) are inhalable particles and small enough to penetrate the thoracic region of the respiratory system. Exposure to PM causes cardiovascular disease, respiratory disease and lung cancer. Dust can decrease vegetation vitality, crop productivity, and forest and ecosystem health (Chaudhary & Rathore, 2019; Kameswaran et al., 2019). Farmer (1993) stated that dust can block stomata and reduce photosynthesis, respiration, transpiration, and plant growth. It can also increase leaf temperature and allow the penetration of phytotoxic gaseous pollutants. Deposition of limestone dust increases topsoil pH, which leads to nutrient deficiency in crops. Dust can also affect corticolous communities such as lichens (Gilbert, 1976; Paoli et al., 2014), bryophytes (Degtjarenko et al., 2016), and microalgae (Štifterová & Neustupa, 2015) by both directly damaging them and indirectly altering their habitat chemical properties. Monitoring, assessing, and preventing processes are crucial in heavily stone producing industrial areas for maintaining good health, wellbeing, and ecosystems as well as for achieving UN Sustainable Development Goals (SDGs).

Dust concentrations and impact are generally monitored and assessed using equipment. This method has relatively high cost and complications; thus, it is often problematic for low-income countries to effectively manage their environmental quality. Alternatively, bioindicators are simpler, inexpensive, and effective tools (Wolterbeek, 2002). Special attention is given to lichens and mosses due to their great accumulation capacity for many pollutants and their high sensitivity to air pollution (Ares et al., 2012; Bargagli et al., 2002; Nash III, 2008; Nimis et al., 2002). Among higher plants, physiological responses in leaves have been investigated (Hajizadeh et al., 2019; Hrotkó et al., 2021; Jia et al., 2021), but pollutant accumulation is often determined using tree bark (Brignole et al., 2018; Drava et al., 2017; Janta & Chantara, 2017). Bark trees that have large surfaces and permanent contact with the air for several years are good indicators of the atmospheric conditions where the trees are growing. The trees are ubiquitous and can be easily collected even by untrained persons (Steindor et al., 2011). The bioindicative method using bark pH is rarely used, and some studies have been performed in Europe on temperate trees such as pine, spruce, ash, and beech (Degtjarenko et al., 2016; Gilbert, 1976; Lötschert & Köhm, 1977; Paoli et al., 2014; Santamaría & Martín, 1997; Steindor et al., 2011; Świercz, 2006) and in China on pine trees (Yuan-Wen et al., 2006). Acidic pollutants (such as SO_2 and NO_2) decrease bark pH, which is known as the acidification effect (Lötschert & Köhm, 1977; Yuan-Wen et al., 2006); in contrast, alkaline pollutants (such as alkaline dust and NH_3) increase it, which is known as the alkalization effect (Degtjarenko et al., 2016; Marmor & Randlane, 2007). This technique is easier and less expensive; thus, bark pH is a promising tool for assessing environmental quality. In addition, finding new effective bioindicators is necessary for monitoring and observing environmental change.

The Naphralan Subdistrict is the pollution control zone. It is one of the most heavily dusted areas in Thailand. Major emission sources of dust in the area are related to cement production, limestone quarrying and stone crushing processes, as well as transportation of raw materials and products by trucks (Makkwao & Prueksasit, 2021; Phetrawech & Thepanondh, 2017; Pimonsree et al., 2009). Previous studies found a prevalence of respiratory symptoms and lung function deficiencies in students at schools near the main industrial area (Moondee et al., 2004; Tummajisakul et al., 2015). Although we have known about dust pollution in this area for a long time, the problem has not been completely solved. Additional studies should be performed to better understand and solve this problem.

Alstonia scholaris is a tropical evergreen tree that is widely distributed across Thailand and other tropical countries. Its leaves have been previously used to study air pollution in India (Muhammad et al., 2014; Singh, 2021), but bark has never been investigated before. Topsoil pH and lichen communities are often used for assessing the impact of alkaline dust. The results of this study will improve our understanding of the impact of dust on vegetation; the obtained information can be implemented to increase environmental quality. The objectives of this study were (i) to observe the potential of the bark pH of *A. scholaris* trees for use as a bioindicator of alkaline dust pollution, (ii) to determine the extent of the impact of dust on topsoil and lichen communities, (iii) to discover the extent of dust impact on vegetation, and (vi) to achieve the SDGs, goal 3 (Good health and well-being), 11 (Sustainable cities and communities) and 15 (Life on land).

Materials and methods

Study area

This study was conducted in an area of approximately 32 km^2 around Naphralan Subdistrict in Saraburi Province, Thailand, approximately 110 km north of Bangkok (Fig. 1). Several communities with approximately 30,000 inhabitants live in the area (https://stat.bora.dopa.go.th). The terrain is plains and mountains with elevations ranging from ca. 20 to 400 m above sea level (m asl). The ten-year (2012 to 2021) average yearly cumulative rainfall was 1,000 mm. Monthly rainfall of more than 100 mm occurred from May to October. The monthly average relative humidity (RH) ranged from 56% (December) to 80% (September), and the monthly average air temperature ranged from 26.7 (December) to 30.8 (April) °C (Fig. SI-1). Prevailing winds blow from the southwest between March and September and from the east or northeast between October and February (Fig. SI-2). This area has been announced as the pollution control zone since 19 April 2004. There are more than 5 limestone quarries, 40 stone crushing plants, and 5 cement plants in the area (Chulamanee et al., 2014; Pimonsree et al., 2009). These industries emit enormous amounts of dust into the environment by the processes of blasting, crushing, fossil fuel combustion, cement production, and transportation (Chulamanee et al., 2014; Makkwao & Prueksasit, 2021; Phetrawech & Thepanondh, 2017; Pimonsree et al., 2009; Sooktawee et al., 2020). The concentrations of PM10 and PM2.5 always exceeded the national standard levels, especially from October to February (Figs. SI-3 and SI-4). The concentrations of other common air pollutants, including CO, NO_2, and SO_2, were much lower than their standard levels, and O_3 occasionally exceeded its standard level (Fig. SI-5).

Sampling site and sample collection

A total of 13 sampling sites were selected. Twelve of them (S1 to S12) were in the polluted area around Naphralan Subdistrict, and one unpolluted site in Khao Yai National Park (S13) was ca. 64 km away (Fig. 1; Table 1). The sampling sites were first chosen based on the direction and distance from the center of the industrial area. Second, they were located near schools or communities, and third, the targeted tree and soil samples were available. Most sites were located in the south and southwest due to being downwind during high dust concentrations (October to February) (Figs. SI-2 and SI-4).

Bark pH varies according to tree species (Öztürk & Oran, 2011; Spier et al., 2010; Steindor et al., 2011); thus, bark samples were collected on a single tree species, the blackboard tree or devil tree, *A. scholaris* (L.) R. Br. It is an evergreen tropical tree that is commonly found in Thailand. This tree is the best candidate because it is widely distributed in the study area. It is found in almost all environments, including industrial, urban, rural, and roadside environments, and on mountains up to ca. 800 m asl. The outer bark (cork) is rough and thick enough to accumulate air pollutants, and it is easy to collect and prepare samples. Bark samples were collected on five freestanding trees at each site, except S7 and S12, where only three trees were available. Only the outer bark (died bark) (Yuan-Wen et al., 2006) with a thickness of 1–3 mm was randomly picked around the trunk at a height between 1.5 and 3 m above the ground, except on the side with an obstruction that prevented free air flow such as a wall, other plants, or an advertising board. Our preliminary study showed that the bark pH of *A. scholaris* at 1, 2 and 3 m above the ground had no statistically significant difference (unpublished data). Because homogeneity of tree diameters was not observed at the sampling sites, bark samples were collected from diverse tree sizes, approximately 25–40 cm in diameter at breast height (1.3 m above ground). Bark samples were detached from tree trunks using a stainless knife and contained in polyethylene plastic bags to prevent water and air contamination. Bark samples were not collected at S3 and S5 because the targeted trees were not discovered or were considered unsuitable. The collection was performed in January 2022.

Soil samples were collected in the same period as the bark collection. Five soil samples were randomly collected at five selected points on open land at each

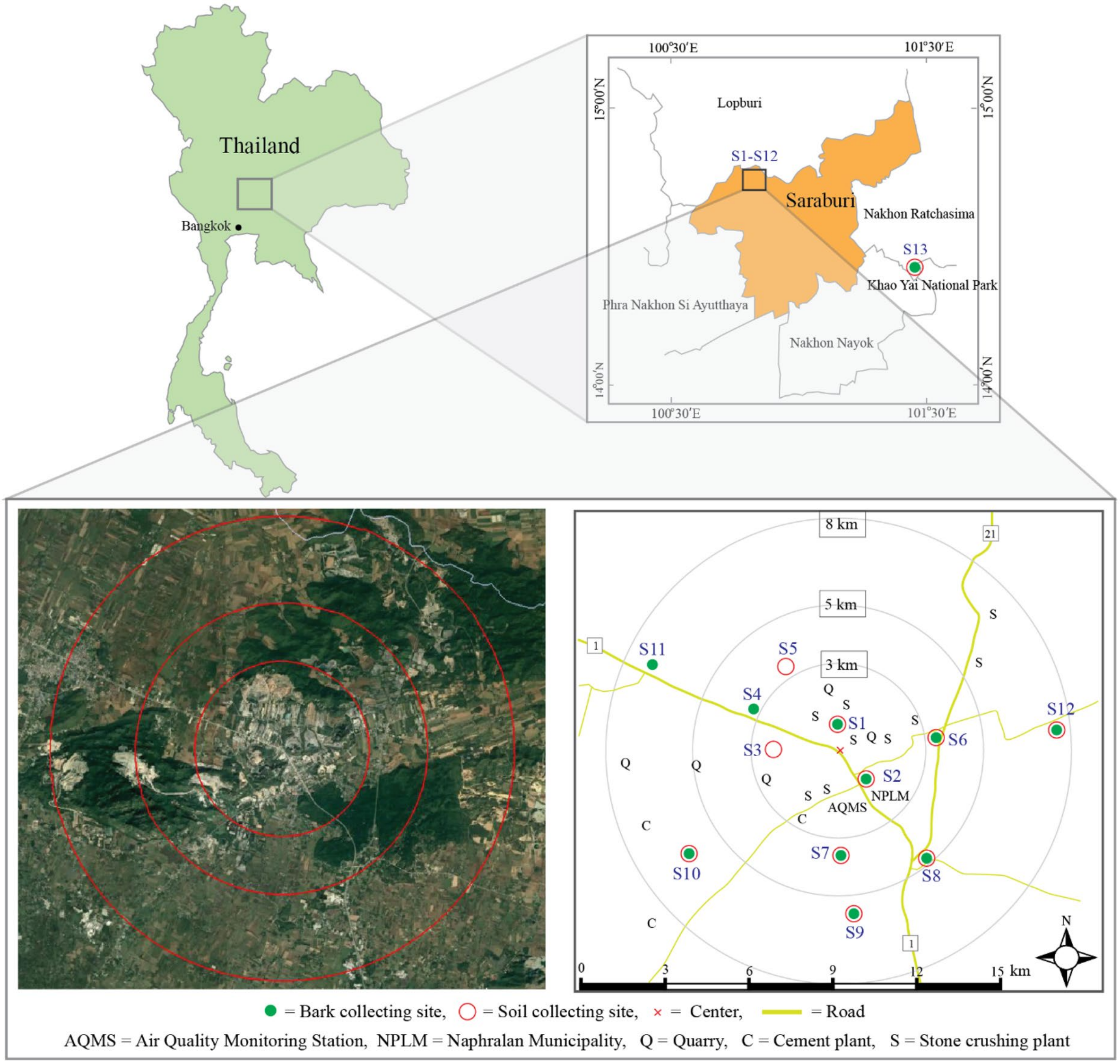

Fig. 1 The study area and twelve sampling sites (S1-S12) around Naphralan Subdistrict in Saraburi Province, Thailand, and one unpolluted site at Khao Yai National Park (S13). Bark samples were not collected at S3 and S5, and soil samples were not collected at S4 and S11. Some representative sites are shown, including quarries (Q), cement factories (C), and stone crushing plants (S)

site. The targeted points were dug in a "V shape" at a depth of approximately 15 cm, and composite soil samples were scooped from the surface to the deepest point of the hole at a thickness of 2–3 cm. Approximately 0.5 kg of soil sample was obtained from each point at each sampling site. Soil samples were collected using a stainless steel shovel and contained in polyethylene plastic bags to prevent water and air contamination. Soil samples were not collected at S4 and S11 because they were not the primary selected sampling sites but were used as alternative sites for bark collection.

Bark pH and soil pH measurements

The measurement of bark pH was slightly modified from Kricke (2002). Each bark sample was oven-dried at 105 °C for 24 h. Then, it was ground using a grinder and sieved through a 2 mm^2 sieve plate. Approximately 1 g of ground bark was soaked in 20 mL of deionized water and covered to prevent carbon dioxide contamination. The mixture was stirred for approximately 10 min and left for 4 h with occasional shaking. pH measurement was performed in the suspension of the mixture

Table 1 Description of sampling sites in the polluted area around Naphralan Subdistrict in Saraburi Province (S1-S12) and in an unpolluted area at Khao Yai National Park (S13). Bark samples were not collected at S3 and S5, and soil samples were not collected at S4 and S11

Sampling site	Location name	Latitude-Longitude[a]	Elevation (m asl)[a]	Distance from the center (km)[b]	Bark collection	Soil Collection
S1	Ban Kungkaokeaw School (BKK)	14°42'14.25"N 100°51'47.88"E	90	0.68	●	○
S2	Naphralan School (NPL)	14°41'20.08"N 100°52'15.88"E	75	1.27	●	○
S3	Ban Subchaom School (BSC)	14°41'54.31"N 100°50'42.50"E	95	2.10	-	○
S4	Ban Thanthongdang School (BTT)	14°42'35.04"N 100°50'5.14"E	85	3.45	●	-
S5	Nikhomsongkhro 2 School (NKS)	14°43'30.74"N 100°50'46.96"E	97	3.57	-	○
S6	Ban Khaoruak School (BKR)	14°42'16.89"N 100°53'50.33"E	77	3.61	●	○
S7	Khao Nok Yung Community (KNY)	14°39'57.68"N 100°52'0.79"E	51	3.63	●	○
S8	Wat Phukhae School (WPK)	14°39'52.48"N 100°53'27.58"E	54	4.72	●	○
S9	Ban Kaodintai School (BKD)	14°38'46.80"N 100°52'7.82"E	34	5.76	●	○
S10	Ban Khaoplad School (BKP)	14°39'53.65"N 100°48'54.24"E	23	6.47	●	○
S11	Boromrajonani College of Nursing Phra Phuthabat (BCN)	14°43'19.46"N 100°48'16.76"E	59	6.95	●	-
S12	Ban Nongchan School (BNC)	14°42'23.47"N 100°55'52.21"E	86	7.28	●	○
S13	Khao Yai National Park (KY)	14°25'30.45"N 101°23'11.79"E	716	63.90	●	○

[a] Data was obtained from Google Earth Pro application

[b] Distances show as linear directions obtained from Google Earth Pro application

using a standard electrode (LE407, Mettler Toledo, Switzerland) and meter (FiveGo, Mettler Toledo, Switzerland) and conducted in a temperature-controlled room at approximately 25 ± 2 °C. Three measurements were performed on each mixture, and an arithmetic mean was calculated. Of note, measuring bark pH by this method generally provides a higher pH value than the surface bark pH measurement using KCl as a solution (Farmer et al., 1990; Kricke, 2002).

The measurement of soil pH followed the procedure of the Land Development Department of Thailand (LDD, 2010). Each soil sample was air dried at room temperature for 3–5 days. After a constant weight was achieved, the sample was ground and sieved through a 1 mm^2 sieve plate. Approximately 20 g of soil powder was submerged in 20 mL of deionized water and covered to prevent carbon dioxide contamination. The mixture was stirred for approximately 10 min and left for 1 h with occasional shaking. pH measurement was performed in the supernatant portion using a standard electrode (LE407, Mettler Toledo, Switzerland) and meter (FiveGo, Mettler Toledo, Switzerland) and conducted in a temperature-controlled room at approximately 25 ± 2 °C. Three measurements were performed on each mixture, and an arithmetic mean was calculated.

Lichen community

The species richness, abundance, and frequency of lichens were documented on the trunks of all *A. scholaris* trees from which bark samples were collected. The data were obtained on a 10×50 cm transparent quadrat divided into five 10×10 cm grids. Four quadrats were obtained on each tree on the north, east, south, and west sides, and each was located between 50 and 150 cm above ground. Subsequently, the lichen diversity value (LDV) was calculated according to Asta et al. (2002). Lichens in the unpolluted site at Khao Yai National Park were not observed because many differences in climatic conditions, such as relative humidity and air temperature, lead to different lichen communities. The comparative site for the lichen community was the farthest site from the center (S12).

Statistical analysis

All data were checked for parametric or nonparametric statistics before the assignment of statistical tests. Normality was tested using the Shapiro–Wilk test. Statistically significant differences between groups of bark pH or soil pH were tested using one-way analysis of variance (one-way ANOVA) with Tukey's test as post-hoc comparison at $p < 0.05$ and Student's t-test. The relationships between bark pH, soil pH and distance were examined using Pearson's correlation. All statistical tests were performed using SigmaPlot 14 (Systat Software Inc., USA).

Results and discussion

The mean bark pH of *A. scholaris* trees at all sites ranged from 4.3 to 7.3, while the absolute values of individual trees ranged from 4.0 to 7.7. The lowest mean value was found in the unpolluted area at Khao Yai National Park and was significantly lower than those at all polluted sites around Naphralan Subdistrict (Fig. 2a, Table SI-1). Among the polluted sites, bark pH ranged from 5.5 to 7.3, in which the lowest value was observed at the farthest site from the center (S12),

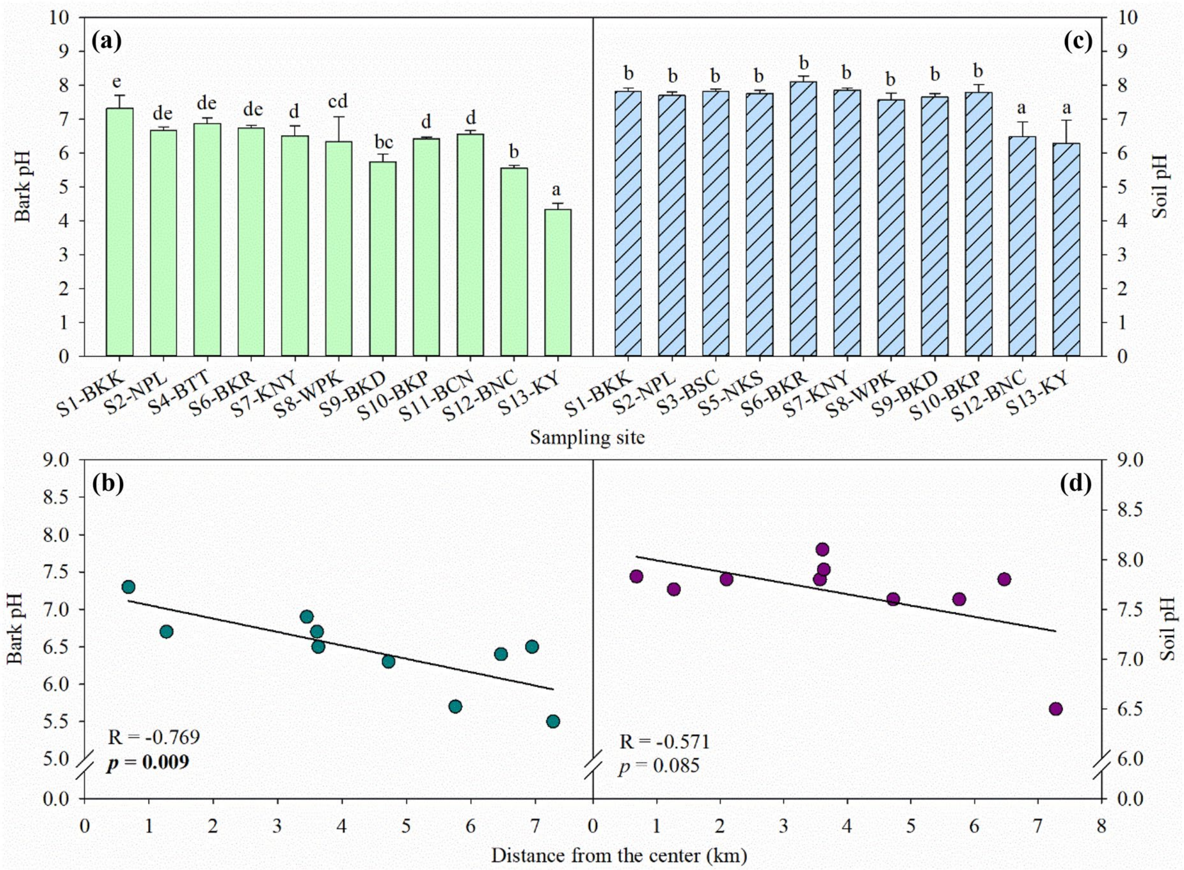

Fig. 2 Bark pH of *Alstonia scholaris* trees collected at the polluted sites around Naphralan Subdistrict in Saraburi Province (S1-S12) and at the unpolluted site in Khao Yai National Park (S13) (**a**), the relationship and Pearson's correlation coefficient (R) between bark pH and distance from the center based on all polluted sites (**b**). Soil pH at all polluted sites (**c**), the relationship between their value and distance from the center based on all polluted sites (**d**). Different letters on the bars indicate statistically significant differences by one-way ANOVA with Tukey's test, $p < 0.05$. Bold p values indicate statistical significance

and the highest value was discovered at the nearest site (S1). Bark pH showed a strongly negative correlation with distance based on all polluted sites ($R = -0.769$, $p = 0.009$, Fig. 2b). The obtained results indicate that bark pH decreases with increasing distance from the main emission source of dust.

The bark pH found in this study was in the range of the bark pH reported in other studies (Table 2). In the polluted area around Naphralan Subdistrict, the highest bark pH value was found at the nearest site (S1) to the center and then tended to decrease at farther sites, which showed the lowest value at the farthest site (S12), which was approximately 7.3 km away. However, this site (S12) was upwind during the high dust concentration period between October and February. At this time, the prevailing wind came from the east or northeast, and the downwind sites belonged to S1, S2, S3, S7, S8, S9 and S10. Site S9, which was approximately 5.8 km away, was a suitable location to measure the extent of dust impact. S10 was not appropriate due to adjacent quarries and cement plants. The bark pH at S9 was 5.7, which was not significantly different from that at S12. Although the pH values of both sites (5.5, 5.7) were still ca. 1.3 times higher than that at the unpolluted site, these values could be accepted as normal values at a community in a rural area. van Herk (2001) reported that the average bark pH of common oak trees (*Quercus robur*) collected in village sites was 5.16, ca. 1.3 times, compared to the forested sites (4.05). The higher bark pH values at S10 and S11 compared to S9 could be explained by the adjacent additional sources of dust. S10 was located near a cement plant approximately 1 km southeast, while S11 was located near a junction of the town of Phra Phutthabat District.

Higher bark pH values near limestone quarries and cement plants were also reported by other scientists from different regions (Table 2). Gilbert (1976) documented that the bark pH of ash trees (*Fraxinus excelsior*) increased with decreasing distance to cement works in England. Values of 6.1–6.5 were observed in the first two kilometers from the plants, and the value dropped to the regular value (ca. 3.5) approximately 5 km away. Świercz (2006) discovered that pine bark pH increased with approaching distance to the cement and lime plants in Poland. Values of 7.2–8.5 were observed within 0.8 km from the plants, and undisturbed values (below 4.0) were observed at distances greater than 5 km. In addition, Paoli et al. (2014) reported that the bark pH of European beech (*Fagus sylvatica*) growing at the limestone quarry in Slovakia was 5.9, which was significantly higher than of 5.3 at 350 m from the quarry. They also noted that the side exposed to the quarry had a significantly higher value (6.1) than the sheltered side (5.7). Degtjarenko et al. (2016) revealed that the bark pH of Scots pine (*Pinus sylvestris*) in Estonia had a significantly higher value at the closest distance to the quarry (6.3) and lower at farther sites. It reached a natural pine bark pH of ca. 3.4 at distances greater than 2 km. The alkalinization effect of dust on tree bark is related to rainfall, stemflow and throughfall (Farmer et al., 1991). Under alkaline air conditions, the bark pH of Norway spruce (*Picea abies*) and Scots pine (*Pinus sylvestris*) in Estonia tended to increase with tree height (Marmor et al., 2010). The highest values were observed at the canopies, and the values seemed to be not different at the lower height of below 6 m above the ground. Similar findings were also reported by Legrand et al. (1996), who found that higher bark pH values occurred at the canopies of silver fir (*Abies pectinnata*) and Norway spruce growing in a national forest in France. Kermit and Gauslaa (2001) also discovered twigs of Norway spruce in Norway. Limestone ($CaCO_3$) quarrying dust, cement dust and that from many roads are highly alkaline, and cement kiln dust has a pH of 12.0 (Darley, 1966; Farmer, 1993). Therefore, rainwater in dusted areas is generally more basic (Khemani et al., 1985) and can alter bark pH and other substrates, i.e., soil and water.

The mean soil pH at all sampling sites ranged from 6.3 to 8.1, and the absolute value of each sample ranged from 5.3 to 8.4. The lowest mean value was observed at the unpolluted site (S13), and the highest value was found at a polluted site, S6 (Fig. 2c). As shown in Table 3, the soil classes ranged from slightly acidic (S12, S13) to moderately basic (S6, S7). The soil pH at all polluted sites, except S12, was significantly higher than that at the unpolluted site. The value at S12, the farthest site from the center, was comparable with the value at the unpolluted site (S13). In the polluted area, the soil pH ranged from 6.5 to 8.1, and the value at site S12 was significantly lower than those at the other sites. The soil pH tended to decrease at sites with longer distance from the center (Fig. 2d).

Dust from the industrial processes around the Naphralan Subdistrict also affects the topsoil. Soil samples at the unpolluted site at Khao Yai National Park were collected on grassland, which provided higher soil pH values (6.3) in comparison with the values obtained from

Table 2 Bark pH values from many tree species growing in undisturbed and disturbed areas react to air pollution via alkalization and acidification effects

Sampled tree	Country	Bark pH		Pollutant	Emission source	Measuring method[a]	Reference
		Undisturbed/ less disturbed area	Highly disturbed area				
Alkalinization effect							
Alstonia scholaris	Thailand	4.3 ± 0.2	7.3 ± 0.4	Alkaline dust	Cement plants, Limestone quarries, Stone crushing plants	H_2O + Standard pH electrode	This study
Fraxinus excelsior	England	3.5	6.1–6.5	Alkaline dust	Cement works	Not mentioned	Gilbert (1976)
Fagus sylvatica	Slovakia	5.3 ± 0.3	5.9 ± 0.3	Alkaline dust	Cement mill, Limestone quarries	H_2O + Standard pH electrode	Paoli et al. (2014)
Pinus sylvestris	Estonia	3.2	6.3	Alkaline dust	Limestone quarry	KCl + Flathead pH electrode	Degtjarenko et al. (2016)
Pine (species not defined)	Poland	2.8–3.5	7.2–8.5	Alkaline dust	Cement plants	H_2O + Standard pH electrode	Świercz (2006)
Pinus sylvestris *Tilia cordata*	Estonia	3.0 4.4	5.3 5.7	Dust (NO_x also a major pollutant but less influence)	Road traffic and urban area	KCl + Standard pH electrode	Marmor and Randlane (2007)
Picea abies *Pinus sylvestris*	Estonia	3.3 3.1	3.8 3.5	Alkaline particulate matter (oil shale ash)	Power plants	KCl + Flathead pH electrode (Values at up to 2 m above the ground)	Marmor et al. (2010)
Quercus robur	Netherlands	4.05 (forest)	5.79 (intensive agricultural) 5.24 (moderate agricultural) 5.16 (village) 4.71 (arable land) 4.40 (town)	Mainly NH_3	Agricultural area Livestock Arable land Village Town	H_2O + Standard pH electrode	van Herk (2001)
Quercus *Ulmus* *Tilia* *Fraxinus*	Netherlands	-	5.20 ± 0.44 5.38 ± 0.37 5.48 ± 0.36 5.65 ± 0.33		Urban area	H_2O + Flathead pH electrode	Spier et al. (2010)
Acidification effect							
Robinia pseudoacacia *Acer pseudoplatanus* *Taxus baccata* *Fraxinus excelsior*	Poland	4.69 ± 0.48 5.31 ± 0.34 4.85 ± 0.27 4.84 ± 0.26	3.86 ± 0.35 4.57 ± 0.50 4.34 ± 0.22 4.48 ± 0.10	SO_2	Heavily industrialized cities	H_2O + Standard pH electrode	Steindor et al. (2011)

Table 2 (continued)

Sampled tree	Country	Bark pH		Pollutant	Emission source	Measuring method[a]	Reference
		Undisturbed/ less disturbed area	Highly disturbed area				
Pinus massoniana	China	Ca. 3.99	Ca. 3.58	SO_4^{2-}/NO_3^-	Smelting industry	H_2O + Standard pH electrode	Yuan-Wen et al. (2006)
Fraxinus excelsior *Acer platanoides* *Tilia* spp. *Acer platanoides*	Germany	3.40–3.50	3.10	SO_2	Urban area	H_2O + Standard pH electrode	Lötschert and Köhm (1977)
Fagus sylvatica *Quercus robur* *Quercus ilex*	Spain	> 5.5 5.0–5.5 5.0–5.5	< 4.5 < 4.5 < 4.5	SO_2	Transportation	H_2O + Standard pH electrode	Santamaría and Martín (1997)

[a] pH measuring using KCl as solvent tend to have lower value in comparison with deionized water or distilled water as the solvent, in addition, pH value also depends on the mass of bark, the volume and quality of solvent (Farmer et al., 1990; Köhler et al., 2015; Kricke, 2002)

soil sampled at forest floor (4.2) due to lower microbial decomposition (unpublished data). Among the polluted sites, the pH value at S12 could be comparable to that at the unpolluted site, while the other sites were 1.2 to 1.3 times higher and categorized as slightly to moderately basic. Singh and Rao (1968) found that dust caused the soil pH to rise from 7.3 to 7.8. Changes in soil pH are considered one of the most important factors affecting the productivity of crops. More alkaline or acidic soil makes minerals unavailable to plants. The optimal range of soil pH for many crop plants is approximately 5.5 to 6.5 (Kameswaran et al., 2019), and more basic soil may lead to deficiencies in iron, manganese, copper, phosphate, and boron (Farmer, 1993).

Table 3 Soil pH classes according to the Land Development Department of Thailand (LDD, 2010)

Sampling site	pH value	Soil class
S1-BKK	7.8 ± 0.1	Slightly basic
S2-NPL	7.7 ± 0.1	Slightly basic
S3-BSC	7.8 ± 0.1	Slightly basic
S5-NKS	7.8 ± 0.1	Slightly basic
S6-BKR	8.1 ± 0.2	Moderately basic
S7-KNY	7.9 ± 0.1	Moderately basic
S8-WPK	7.6 ± 0.2	Slightly basic
S9-BKD	7.6 ± 0.1	Slightly basic
S10-BKP	7.8 ± 0.2	Slightly basic
S12-BNC	6.5 ± 0.4	Slightly acidic
S13-KY	6.3 ± 0.7	Slightly acidic

At the sites where soil and bark samples were both collected, the soil had significantly higher pH values than the bark (Fig. 3a). A similar result was also noticed in Poland by Chrzan (2015). The different gabs between the values at each site was different. The largest different gab (ca. 2.0 pH unit) was discovered at the unpolluted site (S13), which may be a natural property. The different gabs in the polluted sites ranged from 0.5 to 1.9 pH units, and the narrowest gab was found at the nearest site to the center (S1), indicating a high impact of both the cortisphere (relating to bark) and pedosphere (relating to soil). Bark pH showed a strongly positive correlation with soil pH ($R = 0.862$, $p = 0.003$, Fig. 3b), confirming a similar response to the effects of dust pollution.

Lichens are among the most sensitive communities to air pollution; thus, they can provide informative details of the effects of dust on vegetation (Gilbert, 1973; Hawksworth & Rose, 1970; LeBlanc & De Sloover, 1970; Nash III, 2008). A total of 7 lichen species were observed on the investigated trees (*A. scholaris*) in the polluted area around Naphralan Subdistrict (Table 4). They were discovered at only 3 sites, S8, S9 and S12, which were situated approximately 4.7–7.2 km away from the center. No lichens were noticed on the trees at sites less than 4 km. These sites had pH values ranging from 5.5 to 6.3, and the other sites that had higher pH values did not have lichens. The highest number of lichen species was observed at site S12 (4 species), while the LDV at S9 and S12 was comparable and higher than that at the other sites. A previous study by Tummajisakul

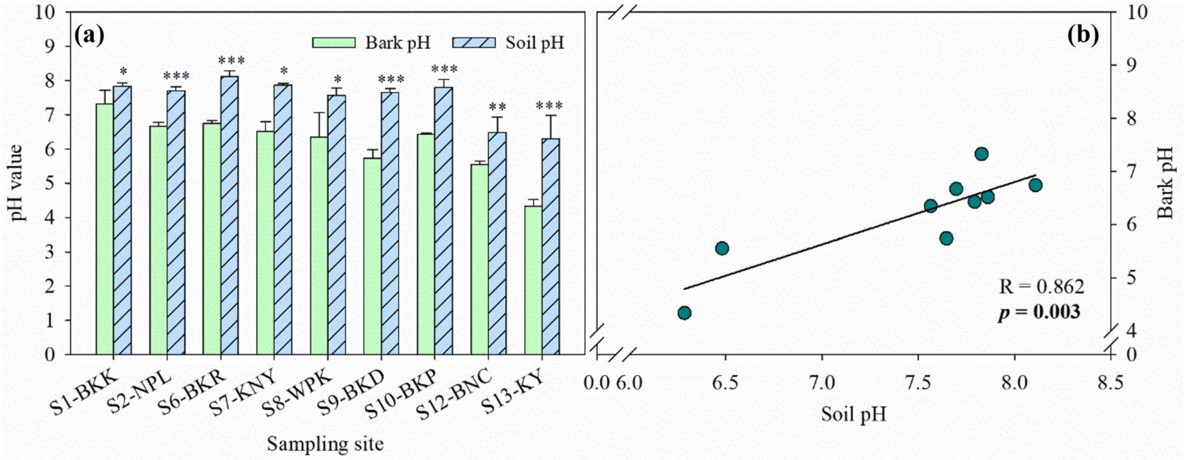

Fig. 3 **a** Comparison between bark pH of *Alstonia scholaris* trees and soil pH obtained from the sampling sites at which both samples were collected. A statistically significant difference of each pair was tested by Student's t-test at $p < 0.05$ (*), $p < 0.01$(**), and $p < 0.001$(***). **b** The relationship and Pearson's correlation coefficient (R) between soil pH and bark pH. The bold p value indicates statistical significance

et al. (2015) performed in a community close to S10 found 4 lichen species, including *Anthracothecium* sp., *Cryptothecia effusa*, *Graphis subassimilis*, and *Pyxine cocoes*. The different species found may be due to different observed phorophytes (host trees). Alkaline dust can both directly and indirectly affect lichen growth and communities. Indirect effect is exerted through the alteration of chemical properties of their substrates. Alkaline dust changes oligotrophic bark (nutrient-poor bark) to eutrophic bark (nutrient-rich bark), which promotes a nitrophilous or basiphilous community but reduces an acidophilous community (Degtjarenko et al., 2016, 2018; Gilbert, 1976; Paoli et al., 2014). In highly polluted areas, dust directly affects all lichen communities and creates lichen deserts (zones without lichens) (Paoli et al., 2014). Decreasing chlorophyll contents and increasing chlorophyll degradation (phaeophytin) were found in the lichen *Physcia adscendens* growing along the higher load of a limestone quarry dust in Greece (Zaharopoulou et al., 1993). Most lichen species disappear approaching the limestone quarries, and high dust concentrations were also reported by Loppi and Pirintsos (2000). Higher concentrations of Ca, Fe and Mg were detected in the thalli of the lichen *Xanthoria parietina* at sites closer to the cement mill in Portugal (Branquinho et al., 2008). In addition, significantly higher concentrations of Ca, Ti,

Table 4 Lichen species, number of thalli, and lichen diversity value (LDV) found on the trunks of *Alstonia scholaris* growing in the sampling sites in the polluted area around Naphralan Subdistrict in Saraburi Province, Thailand

No.	Lichen species	Number of thalli									
		S1-BKK	S2-NPL	S4-BTT	S6-BKR	S7-KNY	S8-WPK	S9-BKD	S10-BKP	S11-BCN	S12-BNC
1	*Arthonia* sp.	-	-	-	-	-	-	-	-	-	1
2	*Buelia* sp.	-	-	-	-	-	-	-	-	-	1
3	*Collema* sp.	-	-	-	-	-	7	-	-	-	-
4	*Graphis* sp.	-	-	-	-	-	2	-	-	-	-
5	*Hyperphyscia adglutinata*	-	-	-	-	-	-	-	-	-	10
6	*Physcia undulata*	-	-	-	-	-	-	12	-	-	-
7	*Pyxine cocoes*	-	-	-	-	-	4	58	-	-	29
Lichen Diversity Value (LDV)		0	0	0	0	0	2.0	3.6	0	0	3.6

Remark: (-) lichen was not found

Fe, V, Al and Ni were observed in the thalli of *X. parietina* growing close to the cement mill and limestone quarries in Slovakia (Paoli et al., 2014). Calcium is considered a good tracer of cement dust (Branquinho et al., 2008; Chulamanee et al., 2014; Paoli et al., 2014), and its high concentration is associated with higher pH values and higher alkaline dust loading areas (Paoli et al., 2014; Świercz, 2006).

Here, we surveyed and estimated the long-term effects of dust pollution emitted from cement factories, stone crushing plants, and limestone quarries on the surrounding environment up to ca. 8 km radius from the center. Our finding was consistent with other previous studies. All investigated parameters (bark pH, soil pH and lichen community) accordingly revealed that the highest dust impact was around the central area, characterized by higher bark pH, higher soil pH, and no lichen. The PM10 distribution model in the area also revealed the highest concentration around the center (Pimonsree et al., 2009). The extent of dust impact on vegetation seemed to be within 6–7 km away from the center, but possible emission sources nearby must be considered. The upwind area during the high dust concentration period (October to February) was less affected. Site S12 had the lowest impact suggested by the lowest bark pH and soil pH and the highest number of lichen species and thalli. Chulamanee et al. (2014) also reported that S12 had the lowest PM10 concentration compared with the other receptors near S1 and S2.

Almost all sampling sites were located in primary schools, with student ages ranging from 3 to 15 years. They are the most sensitive group to air pollution. Previous health studies on students at some schools revealed that most students suffered from respiratory disease and lung function deficiency (Moondee et al., 2004; Tummajisakul et al., 2015). To improve the environmental quality in this area, we recommend improving the quality of the existing buffer zone (greenbelt) and creating new or more zones around all emission sources. Trees are known for their effective removal of dust and other air pollutants (Nowak et al., 2006), and they also create livable cities (McDonald et al., 2016; Xing & Brimblecombe, 2020). Designing barriers or zones and selecting plant species are crucial steps for building effective buffer zones (Barwise & Kumar, 2020; Kasolo & Temu, 2008). For example, selected trees should be evergreen species, tolerant to air pollution, having high dust capturing capacity, dense canopy but air permeable, many leaf layers for better filtering, leaves distributed from near the base to the canopy, tall enough to capture dust emission, long lifespan and strong. Schools, public areas, and communities should grow more evergreen trees and build green walls or greenbelts. In addition, the road network around the area was also the main emission source of dust caused by the transportation of raw materials and products (Phetrawech & Thepanondh, 2017). An appropriate green barrier should be created along the roads and should always have sufficient water to maintain plant health and increase dust capturing capacity.

The results of this study confirm the potential of the bark pH of *A. scholaris* trees as an indicator of the long-term effects of alkaline dust pollution. To our knowledge, this is the first study utilizing *A. scholaris* tree bark as a bioindicator of air pollution. The technique we proposed in this study is a simple and inexpensive method that can be practiced by non-expert to expert investigators. Because this tree species grows nationwide, it can be used to map alkaline dust pollution in Thailand as a whole. In addition, it is also widely distributed in other Southeast Asian countries, Southern China, India, Papua New Guinea, and Northern Australia (GBIF.org); thus, it can be useful for those researchers who are interested in mapping alkaline air pollution using bark pH. This technique can also be applied to other suitable tree species.

Conclusions

The bark pH of *A. scholaris* trees clearly decreased with increasing distance from the center. The soil pH and lichen community also responded in a similar way. Based on the obtained results, we can preliminarily estimate that the extent of dust impact on vegetation was likely within 6–7 km away from the main industrial area. However, possible additional emission sources, traffic vehicles, and wind directions should be considered. Dust contains several toxic elements that can affect human health, vegetation, crop productivity, forest health, and ecosystems. We would recommend improving existing buffer zones (greenbelts) and creating new and more zones around all possible emission sources. The places with higher risk, such as schools, public areas, and communities, should build green walls and grow more suitable trees. Roadside trees and green barriers should be planted along the road network in the industrial area. Finally, this study confirms the potential of the bark pH of *A. scholaris* trees, soil pH and lichen community as effective and reliable indicators for estimating the long-term effects of alkaline dust pollution. The technique is simple and inexpensive, and the tree is widely distributed in many tropical countries; therefore, it is useful for mapping alkaline dust pollution on a larger scale.

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Authors contributions Chaiwat Boonpeng: Conceptualization, data curation, formal analysis, funding acquisition, investigation, methodology, project administration, resources, software, validation, visualization, roles/writing - original draft, writing - review & editing. Pitakchai Fuangkeaw: Investigation, methodology, resources. Kansri Boonpragob: Conceptualization, supervision, validation.

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Declarations

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