

植物监测大气污染及其抗性

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摘要:研究了在佛山市不同污染点东村和五星盆栽的 30 种绿化植物的叶面积、Fv/Fm、叶片细胞膜渗漏率及光合色素含量相对于清洁对照点华南植物园的差异。结果显示,大气污染条件下,绿化植物叶片的生长受到抑制,PS II 最大光化学效率下降,光合色素发生降解,细胞膜受到了伤害。各实验点所有植物叶面积、Fv/Fm 及光合色素含量平均值均为:植物园 > 五星 > 东村,而叶片细胞膜渗漏率平均值为:植物园 < 五星 < 东村,与大气污染程度相一致。方差分析表明,上述指标中叶面积对大气污染最敏感,Fv/Fm 受种间差异影响最小。受大气污染影响,各生理参数的变化具有不相关性。各项生理参数均表现出抗性的种有白桂木 (*Artocarpus hypargyreus*)、环榕 (*Ficus annulata*)、广宁油茶 (*Camellia semiserrata*) 而枫香 (*Liquidambar formosana*) 为敏感种。

关键词:大气污染监测;绿化植物;生理参数;植物抗性

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Air Pollution Monitoring by Plants and Plant Resistance

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Abstracts: Several physiological parameters were compared including leaf area, cell membrane leakage rate, Fv/Fm and photosynthetic pigments content in leaves of 30 species of plants for urban greening, potted in two air polluted sites, Wuxing(WX) and Dongcun(DC), Foshan City, Guangdong Province, and one less polluted site at South China Botanical Garden in Guangzhou(BG) for control. After growing for 3-5 months, the growth of leaves was inhibited and maximal photochemical efficiency of PS II and content of photosynthetic pigments decreased in most plants at two polluted sites in comparison with the less polluted site. The average values of leaf area, Fv/Fm, and photosynthetic pigments content at each site were in the order of BG>WX>DC, while the average values of cell membrane leakage rate were in the contrary. Data analysis showed that leaf area was the most sensitive one to air pollution and Fv/Fm was slightly affected by different species. According to the tested parameters, it is concluded that *Artocarpus hypargyreus*, *Ficus annulata* and *Camellia semiserrata* are resistant species while *Liquidambar formosana* is sensitive one.

Key words: Air pollution monitoring; Plants for urban greening; Physiological parameters; Resistant plant to air pollution

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中国科学院华南植物研究所欧志英参与部分实验并为本文提出许多宝贵意见,在此致谢。

广东是我国经济增长迅速、城市化进程较快的地区,在经济发展的同时也伴随着生态环境的日益恶化。以广东省佛山市南海区为例,据该区环保局公布的数据,2001年南海区煤炭消费总量为1.01 Mt,燃料油消费总量为1.20 Mt,燃料燃烧产生工业废气 $3.46 \times 10^{10} \text{ m}^3$,排放二氧化硫42 185 t,烟尘5 333 t,工业粉尘排放量1 605 t。与2000年相比,废气排放量增加2.6%,二氧化硫增加0.6%,主要排污行业为火力发电业和陶瓷业。2001年,全市平均酸雨频率为75.8%,酸雨量占总雨量的80.9%,降水平均pH值为4.48。与2000年相比,酸雨频率上升19.3%,降水平均pH值下降0.28个pH单位。酸雨频率高于广东省平均水平,且有上升趋势^[1]。目前,植物在监测大气质量和改善环境污染中的作用已日益为人们所重视。植物在吸尘吸噪音、释放氧气、水蒸气和香气方面的作用是其它措施所不及的^[2]。根据植物受大气污染物伤害的不同程度筛选抗性植物,自六、七十年代以来一直是研究热点。研究较多的大气污染物是 SO_2 、 Cl_2 、 NO_x 、 O_3 、PAN、氟化物、粉尘、烟尘等^[3]。采用的检测手段多以叶片外观伤害症状、植株长势等来判断植物受伤害程度。近年又通过叶片解剖形态和生理生化特征来评价植物的抗污能力^[4,5]。本实验在我国主要陶瓷生产基地之一的广东省佛山市选择两个大气污染点,盆栽70余种城市绿化植物进行抗大气污染能力的评估,比较了其中30种绿化植物对大气污染响应的差异,探讨大气污染对植物的伤害及植物的抗性机理,同时为筛选高抗性的城市绿化树种提供参考依据。

1 材料和方法

实验地点 选择佛山市南海区五星和禅城区东村为大气污染点,两试验点周围陶瓷工业发达,因受陶瓷工业废气的影响,当地大气污染比较严重。同时以广州华南植物园为相对清洁对照点。

植物材料 试验盆苗在佛山林科所(位于南海区小塘镇)于2002年3月上盆栽种,苗龄1-2 a,个别种为营养繁殖,土壤、基肥一致。同年6月初,盆苗分别放置于3处试验点,每点每种植物5盆重复,常规水肥管理。2002年9-11月间取当年生成熟叶作各项分析测定。测定植物共30种。

叶面积测定 用CI-302激光叶面积仪测定盆苗自移入试验点后长出的成熟叶片面积,每株测

2至5片叶。

光合色素测定 以80%丙酮提取,分光光度计(Beckman DU-7)测定叶绿素及类胡萝卜素含量^[6]。

细胞膜的渗透率 取数量相等的叶圆片($d=0.65 \text{ cm}$)用蒸馏水浸泡3 h,以DDS-11型电导仪测浸出液在煮沸前后的电导度,计算相对电导率,以百分率表示。

叶绿素荧光测定 采用彭长连等^[7]的方法,用脉冲调制荧光仪(Pulse Amplitude Modulation Fluorometer, PAM, Walz, Germany)测定叶片的叶绿素荧光诱导曲线。原初光(F_0)是用暗适应15 min的叶片在弱调制测量光($0.05 \mu \text{ mol m}^{-2} \text{ s}^{-1}$)诱导下产生的,最大荧光(F_m)则在 F_0 之后用强饱和脉冲($5000 \mu \text{ mol m}^{-2} \text{ s}^{-1}$)激发。采样时间均为上午9点到10点,采回后即时测定。

2 结果和分析

2.1 植物对大气污染的响应

2.1.1 叶面积

叶面积能较为直观地反映植物生长状况。与对照相比(表1),在五星点和东村点生长的植物叶面积均有不同程度减小,植物园对照点、五星点、东村点所测植物叶面积平均值分别为69.64、45.63、36.82 cm^2 。东村点大气污染对植物叶面积影响大于五星点。

与对照相比,各污染点不同植物叶面积减小程度不同,五星点叶面积变化显著的($>50\%$)是腊肠树、盆架树、印度紫檀、海南木莲、枫香,东村为中国无忧树、腊肠树、海南红豆、小叶胭脂、吊灯树、红桂木、猫尾木、乐昌含笑,部分植株叶片已全部脱落。叶面积基本未受影响(变化在11%以下)的种,在五星点是乐昌含笑、菩提树、海南红豆、白桂木、环榕、灰莉、广宁油茶、山茶、仪花、乐昌含笑等,在东村点的叶面积降幅较少(16%-28%)者为环榕、仪花、广宁油茶、细叶榕、菩提树、毛黄肉楠。从两试验点看,桑科(包括菩提树、细叶榕、环榕、傅园榕、红桂木、白桂木和小叶胭脂)和山茶科(包括山茶、广宁油茶和石笔木)的种类叶面积受大气污染影响而变小的程度低,即叶面积变化率较低。

2.1.2 细胞膜渗漏率

细胞膜渗漏率是反映膜系统稳定性的一个重要指标,受大气污染的伤害,植物叶片细胞膜渗漏率也发生变化(表2)。植物园、五星、东村点该指标

表 1 3 个实验点的植物叶面积 (cm²)
Table 1 Leaf area (cm²) of plants grown at three experimental sites

种类 Species	植物园对照点 Control site	五星点 Wuxing	东村点 Dongcun
仪花 <i>Lysidice rhodostegia</i>	23.80±1.31	26.47±0.67(+11.23%)	19.47±1.07 (-18.18%)
山茶 <i>Camellia japonica</i>	24.17±0.33	24.70±2.21(+2.18%)	14.11±0.22 (-41.61%)
广宁油茶 <i>Camellia semiserrata</i>	51.39±3.00	52.50±3.39(+2.15%)	41.13±5.49 (-19.98%)
灰莉 <i>Fagraea ceilanica</i>	34.93±1.86	35.22±1.33(+0.85%)	24.31±4.56 (-30.41%)
环榕 <i>Ficus annulata</i>	109.34±8.42	109.33±2.37(-0.01%)	91.66±5.22 (-16.17%)
白桂木 <i>Artocarpus hypargyreus</i>	35.11±1.35	34.06±1.64(-3.00%)	20.84±0.26 (-40.64%)
海南红豆 <i>Ormosia pinnata</i>	53.74±3.99	49.61±1.88(-7.68%)	19.64±0.18 (-63.46%)
乐昌含笑 <i>Michelia chapensis</i>	64.31±1.91	57.43±1.67 (-10.70%)	25.99±1.96 (-59.59%)
菩提树 <i>Ficus religiosa</i>	114.65±10.00	101.95±9.00(-11.08%)	81.86±5.09 (-28.60%)
石笔木 <i>Tutcheria spectabilis</i>	60.93±0.05	50.02±2.31(-17.90%)	31.79±1.57 (-47.83%)
红桂木 <i>Artocarpus nitidus</i> ssp. <i>lingnanensis</i>	82.36±6.51	63.79±5.99(-22.55%)	43.80±6.98 (53.18%)
铁冬青 <i>Ilex rotunda</i>	25.78±3.80	19.38±0.68(-24.79%)	16.99±3.68 (-34.07%)
细叶榕 <i>Ficus microcarpa</i>	28.19±1.46	21.07±0.47(-25.24%)	21.00±1.60 (-25.49%)
猫尾木 <i>Dolichandrone cauda-felina</i>	95.91±6.83	69.99±6.34(-27.03%)	44.70±0.64 (-53.40%)
傅园榕 <i>Ficus microcarpa</i> var. <i>fuyuensis</i>	33.55±3.82	24.25±0.98(-27.72%)	*
柳叶润楠 <i>Machilus salicina</i>	14.52±1.17	10.18±1.05(-29.84%)	9.10±1.64 (-37.32%)
竹节树 <i>Carallia brachiata</i>	31.07±2.99	19.16±2.89(-38.31%)	*
华润楠 <i>Machilus chinensis</i>	42.20±1.85	25.96±3.15(-38.48%)	22.21±1.46 (-47.35%)
吊灯树 <i>Kigelia africana</i>	60.58±5.43	36.36±3.75(-39.97%)	26.38±5.48 (-56.45%)
小叶胭脂 <i>Artocarpus styracifolius</i>	20.07±1.53	11.91±1.00(-40.66%)	6.96±2.02 (-65.34%)
灰木莲 <i>Manglietia glauca</i>	98.99±6.23	57.96±4.30(-41.44%)	50.50±2.98 (-48.98%)
毛黄肉楠 <i>Actinodaphne pilosa</i>	233.48±21.27	134.72±4.69(-42.30%)	167.36±1.76 (-28.32%)
幌伞枫 <i>Heteropanax fragrans</i>	36.18±1.86	20.62±2.74(-42.99%)	25.21±2.45 (-30.32%)
中国无忧树 <i>Saraca chinensis</i>	180.6±3.08	99.36±2.52(-44.98%)	10.02±0.96 (-94.45%)
刺果番荔枝 <i>Annona muricata</i>	129.63±12.64	70.28±10.14(-45.78%)	*
腊肠树 <i>Cassia fistula</i>	87.81±4.15	40.88±0.44(-53.45%)	31.92±0.65 (-63.65%)
糖胶树 <i>Alstonia scholaris</i>	101.68±7.08	38.68±1.92(-61.96%)	*
印度紫檀 <i>Pterocarpus indicus</i>	55.51±4.64	20.44±4.23(-63.17%)	*
海南木莲 <i>Manglietia hainanensis</i>	104.82±7.73	32.82±3.46(-68.69%)	*
枫香 <i>Liquidambar formosana</i>	60.68±5.26	2.85±0.16(-95.30%)	

* 表示测定时叶片已脱落。All the leaves had fallen when determined.

括号中的数字为相对植物园对照点增加或减少的百分比,下同。Numbers in parentheses are the increased or decreased percentages compared with the control. The same for the following tables.

平均值分别为 :13.87%、12.36%、17.77% , 说明东村的绿化植物叶片细胞膜受大气污染的伤害较大。

与叶面积变化不同的是,各种植物细胞膜渗透率有升有降,因种而异。五星点,植物中膜渗透率明显增加(+41%~48%)的种是傅园榕、菩提树、竹节树等,东村点为海南木莲、幌伞枫、灰莉、华润楠(+77%~145%)。与在植物园点的膜渗透率基本相同的种,在五星点是印度紫檀、华润楠、乐昌含笑、灰莉、中国无忧树和广宁油茶,东村点有乐昌含笑、铁冬青、灰木莲、小叶胭脂、盆架树、石笔木。此外五

星点出现了渗漏明显降低的种:铁冬青、海南红豆、白桂木、柳叶润楠和腊肠树。虽然以往熏气实验中,出现过一些抗性种,其在污染物浓度低于伤害阈值时,渗透率有所降低^[8,9],但是降幅达40%以上的情况还未出现过,原因有待进一步研究。从实验数据看,渗透率下降并非个别,因此即使有实验偶然误差存在,仍不能忽视污染点生长的植物叶片细胞渗透率下降的事实。

2.1.3 光合色素含量

植物叶片叶绿素的含量也受到大气污染影响,

表 2 3 个实验点植物细胞渗漏率的变化
Table 2 Cell membrane leakage rate in leaves of plants grown at three experimental sites

种类 Species	植物园对照点 Control site	五星点 Wuxing	东村点 Dongcun
铁冬青 <i>Ilex rotunda</i>	28.63±1.67	8.33±0.47 (-70.89%)	27.76±3.38 (-3.04%)
海南红豆 <i>Ormosia pinnata</i>	11.09±0.69	3.94±0.25 (-64.46%)	
白桂木 <i>Artocarpus hypargyreus</i>	12.34±0.66	4.86±0.54 (-60.65%)	14.66±1.95 (+18.76%)
柳叶润楠 <i>Machilus salicina</i>	13.86±0.38	7.63±1.86 (-44.94%)	16.86±0.28 (+21.65%)
腊肠树 <i>Cassia fistula</i>	13.55±1.23	7.67±0.08 (-43.37%)	11.23±0.49 (-17.10%)
吊灯树 <i>Kigelia africana</i>	11.93±0.20	8.22±1.01 (-31.11%)	9.57±0.40 (-19.75%)
环榕 <i>Ficus annulata</i>	18.33±0.20	13.97±0.26 (-23.79%)	24.65±4.21 (+34.47%)
刺果番荔枝 <i>Annona muricata</i>	10.34±0.06	8.13±0.53 (-21.41%)	13.97±2.84 (+35.15%)
幌伞枫 <i>Heteropanax fragrans</i>	17.83±1.85	14.63±0.63 (-17.92%)	37.24±1.95 (+108.85%)
猫尾木 <i>Dolichandrone cauda-felina</i>	16.95±2.46	14.36±0.27 (-15.28%)	14.24±0.49 (-15.99%)
毛黄肉楠 <i>Actinodaphne pilosa</i>	18.24±0.30	15.65±2.61 (-14.18%)	14.17±0.55 (-22.29%)
海南木莲 <i>Manglietia hainanensis</i>	13.64±0.48	11.83±0.24 (-13.27%)	33.42±0.81 (+144.92%)
山茶 <i>Camellia japonica</i>	17.48±1.62	15.42±0.60 (-11.75%)	22.79±1.20 (+30.42%)
细叶榕 <i>Ficus microcarpa</i>	17.21±0.02	15.42±0.35 (-10.37%)	21.49±1.52 (+24.91%)
糖胶树 <i>Alstonia scholaris</i>	10.79±1.84	9.85±0.21 (-8.73%)	11.88±1.22 (+10.06%)
灰木莲 <i>Manglietia glauca</i>	15.62±0.27	14.48±0.49 (-7.29%)	15.31±0.39 (-1.98%)
印度紫檀 <i>Pterocarpus indicus</i>	9.56±0.62	9.48±0.16 (-0.78%)	12.66±0.30 (+32.46%)
华润楠 <i>Machilus chinensis</i>	12.03±0.36	12.30±0.11 (+2.26%)	21.37±2.85 (+77.64%)
乐昌含笑 <i>Michelia chapensis</i>	13.75±0.59	14.25±0.18 (+3.64%)	13.17±0.16 (-4.21%)
灰莉 <i>Fagraea ceilanica</i>	14.52±0.42	15.23±0.17 (+4.92%)	27.88±0.98 (+92.04%)
中国无忧树 <i>Saraca chinensis</i>	12.74±0.50	13.94±0.27 (+9.36%)	16.98±1.05 (+33.21%)
广宁油茶 <i>Camellia semiserrata</i>	16.51±0.41	18.33±0.16 (+11.00%)	19.77±0.33 (+19.74%)
小叶胭脂 <i>Artocarpus styracifolius</i>	11.52±0.10	13.00±1.55 (+12.88%)	12.18±0.46 (+5.76%)
仪花 <i>Lysidice rhodostegia</i>	17.02±1.67	19.78±0.31 (+16.21%)	19.80±0.38 (+16.34%)
枫香 <i>Liquidambar formosana</i>	9.25±0.32	10.94±0.59 (+18.31%)	13.69±1.13 (+47.97%)
红桂木 <i>Artocarpus nitidus</i> ssp. <i>lingnanensis</i>	11.05±0.87	13.33±1.77 (+20.63%)	13.57±0.91 (+22.80%)
石笔木 <i>Tutcheria spectabilis</i>	12.38±1.05	15.56±1.07 (+25.70%)	13.99±1.50 (+13.07%)
傅园榕 <i>Ficus microcarpa</i> var. <i>fuyuensis</i>	10.66±1.13	15.06±1.41 (+41.30%)	16.43±1.37 (+54.11%)
菩提树 <i>Ficus religiosa</i>	10.46±0.49	14.87±0.52 (+42.21%)	14.28±0.18 (+36.60%)
竹节树 <i>Carallia brachiata</i>	6.95±2.34	10.28±0.17 (+47.90%)	11.46 ±0.76 (+64.98%)

有些种叶绿素含量上升而有些种则下降,以下降为主(表 3, 4)。植物园对照点、五星点和东村点被测植物叶绿素 a 含量的平均值分别为 :19.83、19.35、16.49 $\mu\text{g cm}^{-2}$, 叶绿素 b 含量的平均值分别为 7.42、7.33、6.27 $\mu\text{g cm}^{-2}$, 东村点叶绿素含量受影响较大。

受大气污染影响,五星点植物叶绿素 a, b 含量降低明显的种有 :印度紫檀、中国无忧树、灰木莲等,东村点的海南木莲、中国无忧树、枫香、乐昌含笑的叶绿素含量也明显低于对照。叶绿素含量与对照相当的种,在五星有柳叶润楠、细叶榕、灰莉、广宁油茶、乐昌含笑、腊肠树等,东村点有小叶胭脂、红桂木、华润楠、石笔木、细叶榕、傅园榕、幌伞枫

等。叶绿素含量上升较多的是五星点的竹节树、毛黄肉楠、铁冬青、小叶胭脂、山茶、海南红豆、红桂木和幌伞枫,东村点的竹节树、腊肠树、环榕和幌伞枫。

类胡萝卜素含量也受大气污染影响(表 5)。多数植物叶片的类胡萝卜素含量在不同实验点变化趋势与叶绿素变化趋势相同,变化幅度相近。植物园对照点、五星点和东村点植物类胡萝卜素含量平均值分别为 :9.49, 9.63, 8.52 $\mu\text{g cm}^{-2}$, 也是东村点受影响较大。

2.1.4 叶绿素荧光参数

叶绿素荧光参数 Fv/Fm 代表叶绿体光系统 II 的原初光能转换效率。因其对样品的无破坏性,反

表 3 3 个实验点的植物叶片叶绿素 a 含量 ($\mu\text{g cm}^{-2}$)
Table 3 Chlorophyll a contents ($\mu\text{g cm}^{-2}$) in leaves of plants grown at three experimental sites

种类 Species	植物园对照点 Control site	五星点 Wuxing	东村点 Dongcun
印度紫檀 <i>Pterocarpus indicus</i>	23.05±0.21	11.31±1.19 (-50.93%)	16.01±1.16 (-30.53%)
中国无忧树 <i>Saraca chinensis</i>	16.77±2.11	9.57±0.64 (-42.92%)	7.67±1.32 (-54.25%)
灰木莲 <i>Manglietia glauca</i>	20.18±2.12	12.92±0.72 (-35.99%)	17.12±0.17 (-15.16%)
柳叶润楠 <i>Machilus salicina</i>	23.30±4.17	16.19±1.46 (-30.53%)	16.89±2.54 (-27.51%)
猫尾木 <i>Dolichandrone cauda-felina</i>	16.69±0.55	11.82±0.51 (-29.15%)	14.82±1.62 (-11.18%)
菩提树 <i>Ficus religiosa</i>	29.09±2.09	21.21±0.11 (-27.09%)	21.92±0.44 (-24.63%)
石笔木 <i>Tutcheria spectabilis</i>	16.46±2.23	12.38±0.68 (-24.81%)	16.12±0.28 (-2.12%)
华润楠 <i>Machilus chinensis</i>	11.49±0.66	8.67±0.12 (-24.55%)	11.20±0.18 (-2.57%)
枫香 <i>Liquidambar formosana</i>	29.38±1.77	22.23±1.66 (-24.35%)	21.01±2.37 (-28.51%)
刺果番荔枝 <i>Annona muricata</i>	24.62±0.13	19.78±2.71 (-19.66%)	
白桂木 <i>Artocarpus hypargyreus</i>	20.11±1.45	16.86±0.21 (-16.16%)	15.04±0.03 (-25.23%)
吊灯树 <i>Kigelia africana</i>	14.28±0.41	12.52±1.35 (-12.32%)	11.32±0.46 (-20.76%)
海南木莲 <i>Manglietia hainanensis</i>	16.40±0.49	14.40±0.92 (-12.21%)	5.11±0.75 (-68.83%)
仪花 <i>Lysidice rhodostegia</i>	27.70±5.51	24.97±3.49 (-9.88%)	22.4±0.35 (-19.15%)
糖胶树 <i>Alstonia scholaris</i>	26.74±3.07	25.15±1.06 (-5.96%)	
细叶榕 <i>Ficus microcarpa</i>	19.98±0.97	18.88±1.55 (-5.51%)	20.05±3.66 (+0.37%)
广宁油茶 <i>Camellia semiserrata</i>	24.86±2.83	24.73±0.85 (-0.51%)	21.55±1.35 (-13.31%)
灰莉 <i>Fagraea ceilanica</i>	16.59±0.80	16.59±0.21 (0.00%)	13.40±1.47 (-19.26%)
乐昌含笑 <i>Michelia chapensis</i>	15.92±0.13	16.12±0.23 (+1.25%)	11.44±1.25 (-28.17%)
腊肠树 <i>Cassia fistula</i>	10.20±1.66	10.53±0.56 (+3.25%)	12.94±0.96 (+26.81%)
环榕 <i>Ficus annulata</i>	16.72±0.08	18.21±0.89 (+8.93%)	19.56±0.78 (+16.96%)
傅园榕 <i>Ficus microcarpa</i> var. <i>fuyuensis</i>	20.51±2.86	22.43±0.39 (+9.36%)	19.64±1.45 (-4.22%)
红桂木 <i>Artocarpus nitidus</i> ssp. <i>lingnanensis</i>	24.27±4.42	29.34±0.71 (+20.91%)	24.75±1.17 (+1.99%)
海南红豆 <i>Ormosia pinnata</i>	21.41±0.22	26.09±0.14 (+21.85%)	15.43±0.53 (-27.95%)
山茶 <i>Camellia japonica</i>	24.31±1.61	30.07±1.17 (+23.71%)	18.10±1.86 (-25.53%)
小叶胭脂 <i>Artocarpus styracifolius</i>	14.21±0.03	19.34±3.39 (+36.11%)	15.06±1.08 (+5.98%)
毛黄肉楠 <i>Actinodaphne pilosa</i>	20.26±2.04	28.84±0.02 (+42.31%)	
铁冬青 <i>Ilex rotunda</i>	25.08±3.08	36.45±0.84 (+45.35%)	20.56±0.42 (-18.04%)
竹节树 <i>Carallia brachiata</i>	16.77±0.96	24.99±0.38 (+49.00%)	21.90±3.12 (+30.60%)
幌伞枫 <i>Heteropanax fragrans</i>	7.37±0.47	17.99±0.46 (+144.14%)	14.20±1.17 (+92.67%)

应灵敏,测定快速^[10],近年来被广泛应用于植物对逆境的响应研究。已有实验数据表明,植物的荧光参数与大气污染程度之间具有一定的相关性,不同植物的荧光参数对大气污染的响应有显著性差别,可以作为环境评价的重要依据^[11,12]。从表 6 看出,同种植物 Fv/Fm 在不同点受大气污染影响后降低程度不同,各实验点所有植物叶片 Fv/Fm 的平均值:植物园对照点 0.71、五星 0.65、东村 0.61,东村点大气污染对该参数影响稍大于五星。

与对照相比,五星点的白桂木、海南红豆、小叶胭脂、幌伞枫、菩提树等 Fv/Fm 值明显降低,东村点降幅明显的则是细叶榕、灰莉、山茶、傅园榕、小叶

胭脂等。五星点降幅较小的是猫尾木、刺果番荔枝、山茶、枫香、灰莉、仪花、柳叶润楠等,其余种均与对照接近。东村点与对照接近的有吊灯树、乐昌含笑、盆架树、灰木莲、红桂木、白桂木、竹节树、中国无忧树、毛黄肉楠。

2.2 不同生理参数受大气污染影响而变化的相互关系
方差分析表明(表 7)各生理参数受植物种类与污染点交互作用的影响极显著,不同实验点间,只有光合色素含量比值的差异不显著。

将各指标的相对值作相关性分析(两污染点相似,以五星为例,见表 8),只有不同光合色素相对含量之间存在显著相关。

表 4 3 个实验点的植物叶片叶绿素 b 含量 ($\mu\text{g cm}^{-2}$)
Table 4 Chlorophyll b contents ($\mu\text{g cm}^{-2}$) in leaves of plants grown at three experimental sites

种类 Species	植物园对照点 Control site	五星点 Wuxing	东村点 Dongcun
灰木莲 <i>Manglietia glauca</i>	9.04±0.92	4.89±0.24 (-45.97%)	6.85±0.39 (-24.26%)
印度紫檀 <i>Pterocarpus indicus</i>	7.68±0.04	4.22±0.43 (-45.04%)	5.84±0.43 (-23.97%)
中国无忧树 <i>Saraca chinensis</i>	6.39±1.08	3.55±0.17 (-44.52%)	3.09±0.76 (-51.61%)
石笔木 <i>Tutcheria spectabilis</i>	6.09±0.88	3.70±0.86 (-39.18%)	6.48±0.81 (+6.56%)
华润楠 <i>Machilus chinensis</i>	2.70±0.03	1.95±0.09 (-27.63%)	3.04±0.37 (+12.44%)
仪花 <i>Lysidice rhodostegia</i>	13.37±2.09	9.67±0.90 (-27.62%)	7.84±0.17 (-41.35%)
菩提树 <i>Ficus religiosa</i>	10.88±0.96	8.01±0.09 (-26.41%)	9.10±0.03 (-16.34%)
猫尾木 <i>Dolichandrone cauda-felina</i>	6.03±0.01	4.76±0.01 (-21.00%)	5.17±0.67 (-14.21%)
枫香 <i>Liquidambar formosana</i>	10.78±0.16	8.79±0.68 (-18.47%)	7.56±1.70 (-29.86%)
白桂木 <i>Artocarpus hypargyreus</i>	7.68±0.79	6.32±0.29 (-17.63%)	6.78±0.33 (-11.66%)
刺果番荔枝 <i>Annona muricata</i>	8.24±0.36	7.10±1.00 (-13.85%)	
糖胶树 <i>Alstonia scholaris</i>	9.85±1.24	8.60±0.58 (-12.76%)	
灰莉 <i>Fagraea ceilanica</i>	9.06±0.13	7.91±0.06 (-12.74%)	6.88±0.47 (-24.13%)
细叶榕 <i>Ficus microcarpa</i>	7.85±0.49	7.09±0.27 (-9.73%)	7.31±1.31 (-6.83%)
海南木莲 <i>Manglietia hainanensis</i>	6.57±0.28	6.37±0.24 (-3.12%)	3.09±0.04 (-53.06%)
乐昌含笑 <i>Michelia chapensis</i>	6.58±0.24	6.43±0.17 (-2.35%)	4.42±0.41 (-32.85%)
腊肠树 <i>Cassia fistula</i>	4.21±0.73	4.14±0.27 (-1.65%)	5.23±0.33 (+24.25%)
广宁油茶 <i>Camellia semiserrata</i>	9.21±1.36	9.13±0.97 (-0.78%)	7.80±0.95 (-15.25%)
红桂木 <i>Artocarpus nitidus</i> ssp. <i>lingnanensis</i>	11.28±0.00	11.88±0.31 (+5.27%)	10.43±0.77 (-7.53%)
环榕 <i>Ficus annulata</i>	6.05±0.07	6.44±0.31 (+6.56%)	6.66±0.26 (+10.09%)
吊灯树 <i>Kigelia africana</i>	4.57±0.16	4.90±0.80 (+7.34%)	4.05±0.30 (-11.26%)
傅园榕 <i>Ficus microcarpa</i> var. <i>fuyuenensis</i>	7.01±1.39	7.69±0.09 (+9.66%)	6.49±0.53 (-7.40%)
柳叶润楠 <i>Machilus salicina</i>	5.16±0.00	6.13±0.67 (+18.81%)	5.68±0.77 (+10.08%)
小叶胭脂 <i>Artocarpus styracifolius</i>	4.95±0.22	6.44±1.32 (+30.09%)	5.26±0.35 (+6.36%)
海南红豆 <i>Ormosia pinnata</i>	7.67±0.49	10.25±0.51 (+33.63%)	6.77±0.22 (-11.75%)
山茶 <i>Camellia japonica</i>	7.48±0.75	10.69±0.74 (+42.86%)	4.61±0.60 (-38.44%)
竹节树 <i>Carallia brachiata</i>	6.43±0.12	9.59±0.64 (+49.05%)	8.47±0.94 (+31.68%)
铁冬青 <i>Ilex rotunda</i>	9.43±0.80	14.17±0.39 (+50.36%)	7.51±0.16 (-20.38%)
毛黄肉楠 <i>Actinodaphne pilosa</i>	6.42±0.55	10.53±0.55 (+63.93%)	
幌伞枫 <i>Heteropanax fragrans</i>	3.96±0.68	8.60±0.08 (+116.96%)	6.85±0.27 (+72.88%)

3 讨论

3.1 大气污染对绿化植物的影响

本实验中,在五星点和东村点的实验植物的各项生理参数平均值一致反映出,植物在东村受损伤程度最大,说明东村的大气环境更不利于植物生长。因为东村陶瓷工业较五星发达,初步测量结果显示东村点大气中二氧化硫及氟化物含量明显高于五星点(结果另文发表)。表明多物种某一生理指标的整体水平可以作为环境监测中的生物指示因子。

3.2 不同植物对大气污染的响应

理论上,根据不同植物在同种污染物作用下的

伤害阈值不同,可以确定不同物种对此污染物的抗性等级^[13]。由于测量大量植株多项指标的伤害阈值不可行,因此可根据污染点与对照点相对值的大小判断植物抗性。实验数据表明,同一植物不同生理指标对环境污染的响应不相同,从而,得到的抗性等级不同,本实验中只有少数生理指标反映出相同的抗性等级,五星点的枫香和刺果番荔枝是敏感种,抗性强的种为白桂木、柳叶润楠、铁冬青、山茶、红桂木、环榕、广宁油茶、乐昌含笑、细叶榕、傅园榕和竹节树;东村点抗性强的种是白桂木、环榕、广宁油茶、幌伞枫、毛黄肉楠,敏感种是海南红豆、中国无忧树、枫香、海南木莲、印度紫檀。另外,菩提树、海南红豆、盆架树、铁冬青、仪花、灰莉等的抗性已

表 5 3 个实验点植物叶片类胡萝卜素的含量 ($\mu\text{g cm}^{-2}$)
Table 5 Carotenoid contents ($\mu\text{g cm}^{-2}$) in leaves of plants grown at three experimental sites

种类 Species	植物园对照点 Control site	五星点 Wuxing	东村点 Dongcun
幌伞枫 <i>Heteropanax fragrans</i>	5.65±0.61	8.86±0.16 (+56.68%)	5.97±0.84 (+5.49%)
毛黄肉楠 <i>Actinodaphne pilosa</i>	9.05±0.75	13.62±0.05 (+50.40%)	8.76±2.04 (-3.25%)
小叶胭脂 <i>Artocarpus styracifolius</i>	6.10±0.21	8.98±1.62 (+47.23%)	7.20±0.42 (+18.12%)
铁冬青 <i>Ilex rotunda</i>	12.42±0.76	18.11±0.34 (+45.87%)	9.91±0.37 (-20.16%)
傅园榕 <i>Ficus microcarpa</i> var. <i>fuyouensis</i>	10.30±0.67	14.17±0.01 (+37.56%)	12.14±1.17 (+17.81%)
红桂木 <i>Artocarpus nitidus</i> ssp. <i>lingnanensis</i>	11.10±0.74	14.89±0.09 (+34.12%)	12.20±0.25 (+9.90%)
竹节树 <i>Carallia brachiata</i>	8.92±0.15	11.13±0.31 (+24.83%)	10.83±1.21 (+21.40%)
吊灯树 <i>Kigelia africana</i>	6.90±0.16	8.24±0.96 (+19.49%)	6.73±0.10 (-2.44%)
海南木莲 <i>Manglietia hainanensis</i>	7.80±0.28	8.61±0.14 (+10.42%)	6.24±1.54 (-19.97%)
广宁油茶 <i>Camellia semiserrata</i>	10.79±0.82	11.85±0.38 (+9.81%)	10.08±0.27 (-6.58%)
白桂木 <i>Artocarpus hypargyreus</i>	8.59±0.32	9.27±0.19 (+7.95%)	8.10±0.31 (-5.69%)
环榕 <i>Ficus annulata</i>	10.46±0.24	11.12±0.03 (+6.36%)	10.75±0.77 (+2.82%)
柳叶润楠 <i>Machilus salicina</i>	7.12±0.03	7.47±0.42 (+4.95%)	7.37±1.18 (+3.54%)
海南红豆 <i>Ormosia pinnata</i>	10.59±0.37	11.04±0.63 (+4.30%)	7.81±0.38 (-26.19%)
山茶 <i>Camellia japonica</i>	10.12±0.20	10.55±0.81 (+4.30%)	9.03±0.28 (-10.80%)
细叶榕 <i>Ficus microcarpa</i>	9.81±0.47	10.23±1.15 (+4.24%)	10.86±1.93 (+10.65%)
糖胶树 <i>Alstonia scholaris</i>	9.97±1.84	10.29±0.55 (+3.24%)	10.80±1.28 (+8.33%)
灰莉 <i>Fagraea ceilanica</i>	8.45±0.08	8.43±0.09 (-0.20%)	6.60±0.26 (-21.91%)
乐昌含笑 <i>Michelia chapensis</i>	9.16±0.24	9.13±0.52 (-0.29%)	6.06±0.51 (-33.84%)
华润楠 <i>Machilus chinensis</i>	3.55±0.24	3.31±0.08 (-6.80%)	3.99±0.27 (+12.41%)
枫香 <i>Liquidambar formosana</i>	11.32±0.94	10.01±0.87 (-11.61%)	7.96±1.32 (-29.67%)
刺果番荔枝 <i>Annona muricata</i>	12.24±0.12	10.74±2.09 (-12.29%)	12.31±2.23 (+0.58%)
猫尾木 <i>Dolichandrone cauda-felina</i>	8.90±0.32	7.66±0.39 (-13.92%)	7.87±1.17 (-11.50%)
石笔木 <i>Tutcheria spectabilis</i>	7.41±0.55	6.18±0.05 (-16.66%)	8.36±0.21 (+12.76%)
菩提树 <i>Ficus religiosa</i>	14.07±0.93	10.89±0.03 (-22.55%)	11.53±0.19 (-18.03%)
仪花 <i>Lysidice rhodostegia</i>	13.36±4.59	9.60±1.90 (-28.11%)	7.77±0.22 (-41.86%)
腊肠树 <i>Cassia fistula</i>	11.38±1.59	7.55±0.26 (-33.67%)	9.92±0.67 (-12.77%)
灰木莲 <i>Manglietia glauca</i>	11.06±0.24	6.92±0.31 (-37.41%)	7.40±0.04 (-33.13%)
中国无忧树 <i>Saraca chinensis</i>	7.76±1.40	4.38±0.17 (-43.53%)	3.33±0.76 (-57.16%)
印度紫檀 <i>Pterocarpus indicus</i>	10.48±0.12	5.76±0.34 (-44.99%)	7.84±0.86 (-25.22%)

有试验^[12,14],其结论与本试验五星点结果较为一致。综合考察两点的植物抗性可知,对两地大气污染抗性强的种是白桂木、环榕、广宁油茶,敏感种为枫香。

3.3 不同检测指标对大气污染的响应及伤害机理探讨

方差分析表明,三地的大气状况使 9 个分析参数中 7 个产生极显著差异,说明,大气污染直接影响这 7 个生理指标,在评价大气污染状况及植物抗性时这些指标均可作为参考。其中,叶面积对大气污染反应最灵敏;Fv/Fm 受种间差异影响最小;叶片细胞膜渗漏率种间变化趋势则明显不一致。

叶面积反映了植株的生长情况,比其他参数更综合地反映出环境对植物的影响。叶面积变小说明

植株生长受到抑制甚至出现早衰。本实验证实叶面积与大气污染显著相关,并且是几个生理参数中反应最灵敏的,因而适合作环境评价及抗性评价指标。

已有大量实验采用细胞膜渗漏率监测植物受污染物伤害情况。SO₂熏蒸实验表明^[8,9],当 SO₂浓度超过一定阈值时,叶组织的渗漏率大增,且渗漏量越大,随后的可见伤害症状越严重,在达到阈值之前,渗漏率随污染物浓度升高而小幅波动;复合熏气实验证明,SO₂和 HF 对植物叶片渗漏率的影响不是增效反应也无拮抗效应^[15]。由此可知叶组织渗漏率能较好地反映植物受损伤程度。本实验中,渗漏率大体反映了大气污染对植物的影响,但出现了渗漏率受大气污染影响而明显降低的情况,可能由

表 6 3 个实验点植物叶片 Fv/Fm 的变化
Table 6 Fv/Fm in leaves of plants grown at three experimental sites

种类 Species	植物园对照点 Control site	五星点 Wuxing	东村点 Dongcun
细叶榕 <i>Ficus microcarpa</i>	0.560±0.055	0.666±0.043 (+18.88%)	0.379±0.014 (-32.36%)
腊肠树 <i>Cassia fistula</i>	0.703±0.016	0.727±0.004 (+3.50%)	0.624±0.032 (-11.23%)
红桂木 <i>Artocarpus nitidus</i> ssp. <i>lingnanensis</i>	0.689±0.057	0.707±0.016 (+2.66%)	0.669±0.008 (-2.91%)
乐昌含笑 <i>Michelia chapensis</i>	0.711±0.014	0.720±0.061 (+1.29%)	0.673±0.014 (-5.33%)
环榕 <i>Ficus annulata</i>	0.733±0.002	0.741±0.002 (+1.12%)	0.628±0.040 (-14.28%)
灰木莲 <i>Manglietia glauca</i>	0.662±0.023	0.662±0.021 (+0.05%)	0.638±0.045 (-3.55%)
毛黄肉楠 <i>Actinodaphne pilosa</i>	0.695±0.020	0.695±0.015 (0.00%)	0.731±0.006 (+5.27%)
华润楠 <i>Machilus chinensis</i>	0.660±0.031	0.653±0.003 (-1.13%)	0.557±0.090 (-15.59%)
石笔木 <i>Tucheria spectabilis</i>	0.728±0.009	0.700±0.027 (-3.78%)	0.653±0.028 (-10.29%)
铁冬青 <i>Ilex rotunda</i>	0.734±0.072	0.704±0.003 (-4.06%)	0.632±0.015 (-13.86%)
海南木莲 <i>Manglietia hainanensis</i>	0.735±0.006	0.697±0.011 (-5.10%)	0.611±0.024 (-16.88%)
傅园榕 <i>Ficus microcarpa</i> var. <i>fuyuenensis</i>	0.752±0.004	0.712±0.004 (-5.33%)	0.559±0.051 (-25.60%)
竹节树 <i>Carallia brachiata</i>	0.716±0.027	0.678±0.029 (-5.38%)	0.707±0.048 (-1.34%)
中国无忧树 <i>Saraca chinensis</i>	0.658±0.029	0.618±0.007 (-6.08%)	0.664±0.031 (+0.85%)
广宁油茶 <i>Camellia semiserrata</i>	0.756±0.003	0.709±0.012 (-6.28%)	0.664±0.006 (-12.22%)
印度紫檀 <i>Pterocarpus indicus</i>	0.752±0.047	0.699±0.021 (-7.09%)	0.609±0.034 (-18.99%)
吊灯树 <i>Kigelia africana</i>	0.713±0.019	0.660±0.022 (-7.42%)	0.644±0.018 (-9.58%)
糖胶树 <i>Alstonia scholaris</i>	0.730±0.005	0.659±0.026 (-9.68%)	0.704±0.008 (-3.58%)
柳叶润楠 <i>Machilus salicina</i>	0.631±0.029	0.563±0.035 (-10.76%)	0.540±0.039 (-14.38%)
仪花 <i>Lysidice rhodostegia</i>	0.750±0.006	0.665±0.023 (-11.24%)	0.597±0.019 (-20.34%)
灰莉 <i>Fagraea ceilanica</i>	0.801±0.006	0.710±0.035 (-11.31%)	0.547±0.064 (-31.66%)
枫香 <i>Liquidambar formosana</i>	0.766±0.001	0.678±0.001 (-11.52%)	0.652±0.015 (-14.83%)
山茶 <i>Camellia japonica</i>	0.710±0.020	0.628±0.022 (-11.58%)	0.505±0.043 (-28.93%)
刺果番荔枝 <i>Annona muricata</i>	0.705±0.010	0.621±0.004 (-11.93%)	0.614±0.010 (-12.94%)
猫尾木 <i>Dolichandrone cauda-felina</i>	0.680±0.004	0.580±0.037 (-14.75%)	0.547±0.039 (-19.68%)
菩提树 <i>Ficus religiosa</i>	0.663±0.026	0.546±0.047 (-17.60%)	0.527±0.002 (-20.51%)
幌伞枫 <i>Heteropanax fragrans</i>	0.746±0.008	0.585±0.085 (-21.48%)	0.656±0.004 (-12.03%)
小叶胭脂 <i>Artocarpus styracifolius</i>	0.773±0.033	0.518±0.048 (-32.99%)	0.581±0.023 (-24.92%)
海南红豆 <i>Ormosia pinnata</i>	0.703±0.019	0.446±0.027 (-36.60%)	0.597±0.030 (-15.07%)
白桂木 <i>Artocarpus hypargyreus</i>	0.723±0.079	0.427±0.053 (-40.95%)	0.711±0.003 (-1.62%)

表 7 不同物种不同实验点及其交互作用对各参数影响的 F 值及其显著性水平

Table 7 F values and their significances for the effects of different species and experimental sites and their interactions on leaf area, membrane leakage rate, Fv/Fm and contents of photosynthetic pigments in plants

分析项目 Analytic items	实验点 Site (Df=2)	物种 Species (Df=29)	污染点×物种 Site × species (Df=58)
叶面积 Leaf area	1329.24****	1008.47****	89.12****
细胞渗漏率 Cell membrane leakage rate	154.23***	130.84****	132.91****
Fv/Fm	231.44****	19.73***	11.99***
叶绿素 a Chlorophyll a	44.73***	54.44****	9.43***
叶绿素 b Chlorophyll b	41.55***	59.43****	10.67***
叶绿素 a+b Chlorophyll a+b	45.76***	58.14****	10.36***
类胡萝卜素 Carotenoid	24.67**	33.64****	5.92***
叶绿素 a/b Chlorophyll a/b	2.01	37.64****	6.38***
叶绿素 / 类胡萝卜素 Chl / Car	3.78*	28.24****	6.36***

* P≤0.05; ** P≤0.01; *** P≤10⁻¹⁰; **** P≤10⁻³⁰.

表 8 各指标相对值之间的相关性
Table 8 Correlation index between relative values of items

项目 Items	叶面积 Leaf area	细胞膜渗漏率 Cell membrane leakage rate	Fv/Fm	叶绿素 a Chlorophyll a	叶绿素 b Chlorophyll b	叶绿素 a+b Chlorophyll a+b	类胡萝卜素 Carotenoid
叶面积 Leaf area	1	-0.034	-0.110	-0.092	0.045	0.188	0.062
细胞膜渗漏率 Cell membrane leakage rate		1	0.240	-0.098	-0.246	-0.146	-0.098
Fv/Fm			1	-0.159	-0.184	-0.070	-0.141
叶绿素 a Chlorophyll a				1	0.926**	0.786**	0.780**
叶绿素 b Chlorophyll b					1	0.850**	0.822**
叶绿素 a+b Chlorophyll a+b						1	0.823**
类胡萝卜素 Carotenoid							1

*: Correlation index ≥ 0.361 ; **: Correlation index ≥ 0.463 (Df=28)

于对照点存在其他胁迫因子导致某些种的渗漏率上升,其原因有待进一步研究。因此,该生理参数用于评价大气污染状况或植物抗性时须同时考虑其他参数。

叶绿素荧光参数和光合色素含量均是与光合作用有关的生理指标。叶绿素荧光参数已成功的用于检测大气中臭氧对植物的损伤及植物对臭氧的抗性评价^[16-18],但是关于污染物导致荧光参数 Fv/Fm 降低的机理,目前仍无定论。另外需指出的是,不同胁迫条件下,植物所需暗适应的时间会有所差异,暗适应时间过长或过短都会造成误差^[19],降低数据可比性。叶绿素丧失与大气污染有关,其机理有多种假设:Lenzian^[20]认为 SO₂ 使叶缘与叶脉间叶绿体分解,叶绿素破坏。Hallgren^[21]认为 SO₂ 诱导叶绿素酶解,产生脱植基叶绿素。Ziegler^[22]的研究则表明,SO₂ 熏蒸产生了脱镁叶绿素,还有一种说法是,SO₂ 诱导产生自由基,进而造成叶绿素的破坏^[23]。Sakaki 等^[24]研究表明,Chla 比 Chlb 对自由基更敏感,因而 Chla/Chlb 的下降能够作为自由基假说的证据,陈小勇^[25]、张其德等^[26]对个别物种熏蒸实验结果表明 SO₂ 作用下 Chla 比 Chlb 略敏感。本实验中,方差分析表明,Chla/Chlb 受污染物影响不显著,据此推测自由基诱导可能不是造成叶绿素损失的主要原因,对苔藓及多种高等植物的研究^[22, 26, 27]表明叶绿素被漂白产生脱镁叶绿素的说法似乎更合理。另外,叶绿素相对含量与相对荧光参数之间不存在相关性,证明叶绿素含量在一定范围内的丧失不会影响光合作用,卢从明等研究的结果^[28]也表明叶片衰老过程中 Fv/Fm 降低明显滞后于叶绿素含

量的降低。

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