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6种叶菜吸附颗粒物与叶片微形态特征研究

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摘要:【目的】叶菜作为一种特殊的绿色植物,不仅在农业生态系统物质循环和能量流动中发挥着关键作用,而且作为一种大气-土壤交界的重要环境界面,具备显著消减大气颗粒物浓度的生态功能。本研究对杭州市6种常见叶菜叶片不同粒径颗粒物吸附量及叶表微形态特征进行分析,以期为利用叶菜表征区域大气颗粒物污染提供参考依据。【方法】选取青菜 *Brassica chinensis* L、菠菜 *Spinacia oleracea* L、生菜 *Lactuca sativa* var. *crispa*、苋菜 *Amaranthus tricolor* L. 杭白菜 *Brassica chinensis* var. *oleifera*、叶用番薯 *Ipomoea batatas*,采用水洗测量法测定植物表面不同粒径颗粒物吸附量,利用扫描电镜观察叶菜表面的微形态结构,探究叶片表面微形态与颗粒物吸附能力的关系。【结果】(1)不同叶菜叶表面对总颗粒物的吸附能力存在差异,以叶用番薯吸附总颗粒物的能力最强((22.62±4.15)μg/cm^2),生菜吸附能力最弱(6.46±1.22)μg/cm^2)。(2)通过比较叶菜对不同粒径颗粒物的吸附量可知,以叶用番薯对$PM_{>10}$、$PM_{2.5\sim10}$及$PM_{0.2\sim2.5}$的能力最强,以生菜吸附$PM_{>10}$的能力最弱,以杭白菜吸附$PM_{2.5\sim10}$能力最弱,以苋菜吸附$PM_{0.2\sim2.5}$能力最弱。(3)叶菜叶片以吸附$PM_{>10}$为主,占总颗粒物质量的75.19%~88.42%,$PM_{2.5\sim10}$占总颗粒物质量的7.75%~22.93%,$PM_{0.2\sim2.5}$占总颗粒物质量的1.87%~4.19%。(4)通过线性拟合可知,气孔长度、气孔宽度与$PM_{>10}$质量呈显著性关系,气孔宽度与$PM_{0.2\sim2.5}$质量呈显著性关系,本研究结果可为利用叶菜表征区域大气颗粒物污染提供参考依据。【结论】叶用番薯吸附总颗粒物的能力最强,生菜吸附能力最弱。气孔是影响叶菜吸附不同粒径颗粒物的重要因素。

关键词:叶菜;颗粒物;微形态;气孔
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A Study on Six Kinds of Leafy Vegetables Adsorbing Particulate Matter and Their Leaf Surface Morphology Characteristics

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Abstract:[**Objective**]As a special green plant,leafy vegetable not only plays an important role in materi-

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al circulation and energy flow in agricultural ecosystem, but also as a key environmental interface between atmosphere and soil, it has the ecologic function of alleviating the concentration of atmospheric particulates. In this study, the capability of 6 common species of leafy vegetables in Hangzhou atmospheric particulate matter(PM) to capture and their micromorphological characteristics of leaf surfaces were investigated, so as to provide a scientific basis for controlling regional atmospheric particulate pollution by leafy vegetables. [**Method**] *Brassica chinensis* L, *Spinacia oleracea* L, *Lactuca sativa* var. *crispa*, *Amaranthus tricolor* L, *Brassica chinensis* var. *oleifera and Ipomoea batatas* were collected. The quantity of plant surface particles were determined by water-washing measurement method. The micromorphological structures of plant surface were observed using a scanning electron microscope. The relationship between PM capturing capability and the micromorphological characteristics of plant surface were explored. The results showed that the total PMs absorbed by leafy vegetable surface varied among different species. [**Result**] (1) *Ipomoea batatas* had the strongest capability to capture total PM (22.62±4.15) μg/cm^2. *Lactuca sativa* var. *crispa* had the weakest capability of capturing total PM (6.46±1.22) μg/cm^2. (2) Comparison of the capability of capturing particulates of different sizes by leafy vegetable surface showed that *Ipomoea batatas* had the strongest capability to capture $PM_{>10}$, $PM_{2.5-10}$ and $PM_{0.2-2.5}$, *Lactuca sativa* var. *crispa* had the weakest capability to capture $PM_{>10}$, *Brassica chinensis* var. *oleifera* had the weakest capability to capture $PM_{2.5-10}$, *Amaranthus tricolor* L had the weakest capability to capture $PM_{0.2-2.5}$. $PM_{>10}$ was the main principal component of the TSP, the percentages of $PM_{>10}$, $PM_{2.5-10}$ and $PM_{0.2-2.5}$ were about 75.19%-88.42%, 7.75%-22.93%, and 1.87%-4.19% respectively, in the total amount of PM. By linear fitting analysis it was found that there was a significant correlation between stoma length, stoma width and the mass of $PM_{>10}$, there was a significant correlation between stoma width and the mass of $PM_{0.2-2.5}$. This study provides scientific evidence for using leafy vegetable to control regional atmospheric PM pollution. [**Conclusion**] *Ipomoea batatas* had the highest capability to capture total particulate matter, *while Lactuca sativa* var. *crispa* had the weakest capability to capture total PM. Stoma was an important influencing factor in the adsorption of particulates of different sizes by leafy vegetables.

Keywords: leafy vegetable; particulate matter; micromorphology; stoma

【研究意义】随着城市化和工业化的迅速发展,大气颗粒物污染已经严重影响到城市环境和人类健康。研究发现,城市绿化植物叶片通过吸附或滞留大气颗粒物的方式,以减少或控制大气颗粒物含量,发挥改善空气质量的功能[1-2]。【前人研究进展】大气颗粒物是有毒有害物质的载体,能够通过叶面气孔的主要途径吸收大气颗粒物中携带的污染物,例如重金属[3-4]、多环芳烃[5]、黑碳[6],其中一部分存在于叶片表面,一部分被固定于植物蜡质层中。由此可见,利用植物吸收大气污染物实现改善空气质量被认为是一种生态友好型的控制手段[7-8]。近年来,利用植物监测大气环境的报道较多,大量研究集中在绿化植物对不同粒径颗粒物的吸附效应上。【本研究切入点】叶菜作为一种特殊的绿色植物,不仅是人类日常生活的重要组成部分,而且在农业生态系统物质循环和能量流动中发挥着关键作用。目前研究已表明,大气颗粒物负载的重金属已成为我国蔬菜中重金属积累的重要来源之一[9-11],其中25%~40%的植物重金属来源于受污染区域大气沉降颗粒物[12-13]。在工业污染密集区域大气沉降是农作物中Cd、Pb、As和Hg等重金属的重要来源[14]。综上所述,叶菜叶片重金属含量存在超标现象,究其原因可能与其庞大的叶表面为大气颗粒物及其携带的污染物进入体内提供了更大的可能[15-16]。叶菜作为一种大气-土壤交界的重要环境界面,同样具备显著消减大气颗粒物浓度的生态功能。【拟解决的关键问题】目前,关于定量研究叶菜对吸附大气颗粒物的特征和机理研究却鲜有报道。鉴于此,本研究对杭州市6种常见叶菜叶片不同粒径颗粒物吸附量及叶表微形态特征进行分析,以期为利用叶菜表征区域大气颗粒物污染提供参考依据,同时为今后探究颗粒物中重金属对叶菜食用安全和农业生态系统扰动机制提供技术支撑。

1 材料与方法

1.1 试验材料

供试6个叶菜品种分别为青菜*Brassica chinensis* L.、菠菜*Spinacia oleracea* L.、生菜*Lactuca sativa* var. *crispa*、苋菜*Amaranthus tricolor* L.杭白菜*Brassica chinensis* var. *oleifera*、叶用番薯*Ipomoea batatas*,均种植于杭州市农科院基地。

1.2 试验方法

1.2.1 样品采集 选择晴朗天气种植6种叶菜,每种叶菜种植12颗。栽培期间添加适当自来水以保持土壤湿度,切勿对叶片进行喷洒灌溉,以保证叶片表面颗粒物的完整性。待叶菜成熟后选择晴朗无风天气统一进行采集,且采样前2周内无降雨和大风等极端天气。分别在各叶菜东、南、西、北4个方向选择叶面积相近、生长状况良好的健康叶片作为样本,每种叶菜分别采集约60片叶片,分3组用于重复试验。样品采集后小心装入自封袋中带回实验室,置于4 ℃冰箱中保存备用待分析。

1.2.2 测定指标及方法 分别将试验所需的10、2.5和0.2 μm的纤维滤网进行编号,随后放置于60 ℃烘箱中烘干至恒重(2 h),置于万分之一天平上称量得到各孔径滤膜的初始质量,记作W_1。先用约300 mL的超纯水浸泡采集的叶片。通过超声波清洗器将附着于叶片的颗粒物震荡溶于超纯水中,用镊子轻轻夹出叶片置于200 mL超纯水中,再用毛刷轻刷叶片上下表面2~3次,合并2次悬浊液。不同粒径颗粒物测定方法参照Xu等[17]。用已烘干的不同孔径滤膜放置在直径47 mm的真空抽滤装置(R300E,美国Sciencetool)中依次用10、2.5和0.2 μm的亲水性滤膜(EMD Milipore USA)进行3次分级抽滤,得到的载尘滤膜放置烘箱中烘干至恒重(60 ℃,6 h)。再用万分之一天平称量,分别得到各滤纸质量W_2。用差量法分别计算各样本中不同粒径颗粒物质量。采用3000c型叶面积仪计算叶面积(S),计算单位叶片面积吸附颗粒物质量。叶菜叶片每单位面积吸附颗粒物量为$W=(W_2-W_1)/S$。

选取清洗干净后的叶片,用刀片避开叶脉切割成5 mm×5 mm的正方形若干,分为上下表面分别制样。用真空冷冻干燥机(−83 ℃)干燥36 h。样品干燥后经过喷金处理,采用环境扫描电镜(FEI Quanta-200,美国FEI公司)观察叶片表面微结构。用Image J软件(国立卫生研究院,美国)量化单位面积叶片上气孔长度和气孔宽度。

1.3 数据分析

数据处理分析应用SPSS 19.0软件,计量采用均数±标准差表示。为验证不同叶菜叶片吸附不同粒径颗粒物的种间差异,对上述参数进行了单因素方差分析(One-way,ANOVA),并采用了最小显著性差异法(least significant difference,LSD,$P<0.05$)进行检验。并进行双因素方差(Two-way Anova)分析不同粒径颗粒物质量与微形态各指标间的关系。

2 结果与讨论

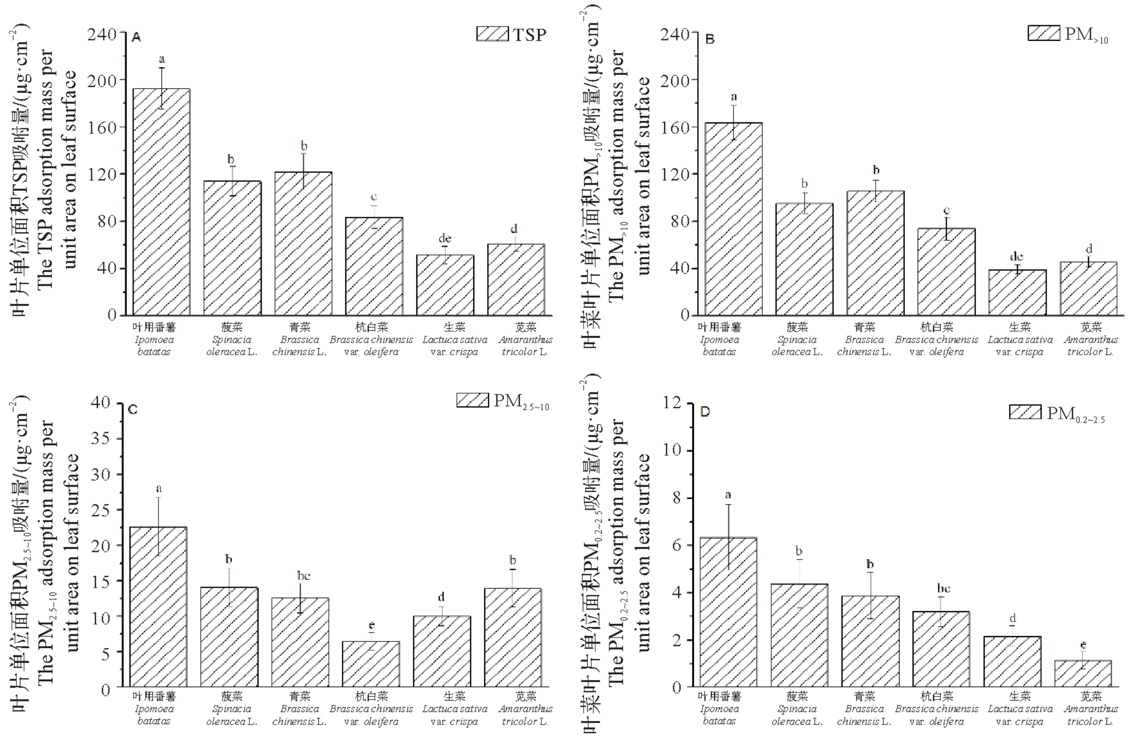
2.1 不同叶菜总颗粒物吸附量

研究表明,本研究测定的6种叶菜总颗粒物吸附量存在差异(图1A)。6种叶菜叶片单位面积TSP吸附量由大到小依次为叶用番薯、青菜、菠菜、杭白菜、苋菜和生菜。其中叶用番薯单位面积PM吸附量最大,为(192.31±17.46) μg/cm^2,生菜吸附量最小,为(51.35±7.67) μg/cm^2。叶用番薯单位面积PM吸附量是生菜的3.75倍。韩营[18]2019年研究发现南方和北方秋季青菜叶表面吸附颗粒物平均含量分别为111 μg/cm^{2}和303 μg/cm^2,表明叶菜叶片对大气颗粒物的吸附易受到叶菜生长环境的影响。林鑫涛等[19]研究发现青冈、冬青、红花檵木对颗粒物平均吸附量在30.4~63.7 μg/cm^2,低于本研究结果。刘延惠等[20]研究发现乔木和灌木2种生活型树种叶面悬浮总颗粒物吸滞量为1.56~11.14 μg/cm^2,低于本研究结果。

2.2 叶菜对不同粒径颗粒物吸附量的比较

不同品种叶菜对不同粒径颗粒物的吸附量存在显著差异。6种叶菜单位面积吸附$PM_{>10}$的能力由大到小表现为叶用番薯、青菜、菠菜、杭白菜、苋菜和生菜(图1B),其中叶用番薯和青菜对大颗粒物的吸附量显著大于其他4种叶菜,比附吸附能力最小的生菜分别高出4.16倍和2.69倍。6种叶菜叶片单位面积吸附$PM_{2.5\sim10}$的能力由大到小表现为叶用番薯、菠菜、苋菜、青菜、生菜和杭白菜(图1C),其中吸附量最大

的叶用番薯(22.62±4.15) μg/cm², 吸附量最小的杭白菜(6.46±1.22) μg/cm², 叶用番薯高出杭白菜3.50倍。6种叶菜叶片单位面积吸附细$PM_{0.2\sim2.5}$的能力由大到小表现为叶用番薯、菠菜、青菜、杭白菜、生菜和苋菜(图1D), 其中吸附量最大的叶用番薯(6.34±1.39) μg/cm², 吸附量最小的苋菜(1.13±0.37) μg/cm², 叶用番薯高出苋菜5.61倍。总体而言, 叶用番薯对PM、$PM_{>10}$、$PM_{2.5\sim10}$及$PM_{0.2\sim2.5}$的吸附量最多, 生菜对PM和$PM_{>10}$的吸附量最少, 杭白菜对$PM_{2.5\sim10}$的吸附量最少, 苋菜对$PM_{0.2\sim2.5}$的吸附量最少。大量研究表明, 植物叶片微形态特征是导致其吸附颗粒物差异的重要因素[21]。



小写字母表示单位叶面积不同粒径颗粒物吸附量在P=0.05水平上差异显著。

Lowercase letters indicate significant differences in particle adsorption per unit leaf area for different particle sizes at the P=0.05 level.

图1 叶菜叶片单位面积颗粒物吸附量

Fig.1 The adsorption particulate matter mass per unit area on leave surface

2.3 叶菜对不同粒径颗粒物吸附量百分比的比较

由图2可知, 叶菜叶片以吸附$PM_{>10}$为主, 占总颗粒物质量的75.19%~88.42%, $PM_{2.5\sim10}$占总颗粒物质量的7.75%~22.93%, $PM_{0.2\sim2.5}$占总颗粒物质量的1.87%~4.19%。李春义等[8]研究发现湿地植物叶面以滞留10~100 μm的颗粒物为主, 占PM组分的64.2%~87.1%。Dzierzanowsi等[22]研究发现植物叶面吸附颗粒物以10~100 μm粒径为主, 其次是2.5~10 μm, <2.5 μm的最少。木尼拉[23]研究发现$PM_{>10}$占总颗粒物的70.58%~97.37%, 粗颗粒物$PM_{1\sim10}$占总颗粒物的比例为2.60%~29.42%, 刘延惠等[20]研究发现叶面吸滞的大颗粒物($PM_{10\sim100}$)和粗颗粒物($PM_{2.5\sim10}$)质量百分比为97.36%, 而对细颗粒物($PM_{1.0\sim2.5}$)和超细颗粒物(PM_1)吸滞能力较弱。王琴等[24]研究发现各乔木

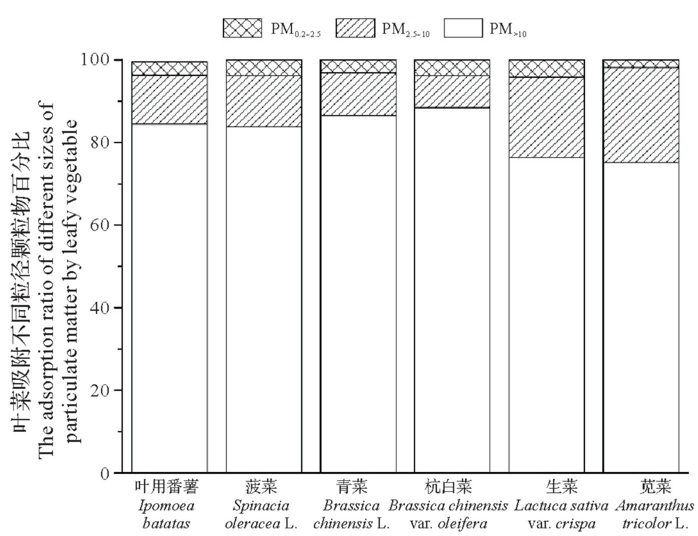


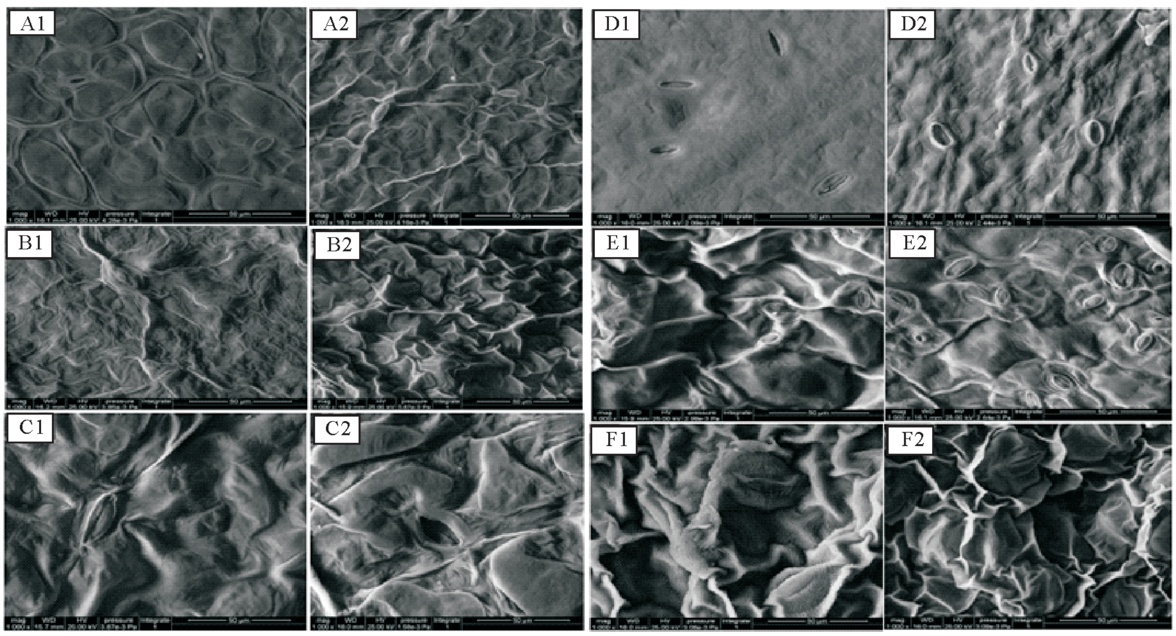
图2 叶菜对不同粒径颗粒物吸附量比例

Fig.2 The adsorption ratio of different sizes of particulate matter by leafy vegetable

单位叶面积滞留$PM_{2.5}$和PM_{10}质量分别占总粉尘量的0.7%~8.9%和3.6%~33.9%,与本研究结论类似。综上所述,叶菜叶表面对不同粒径颗粒物的吸附特征与城市绿化植物一致,主要以吸附$PM_{>10}$为主,$PM_{2.5\sim10}$其次,$PM_{0.2\sim2.5}$最少。

2.4 叶菜叶表面微形态

植物吸附$PM_{2.5}$等大气颗粒物的影响因素有很多,与自身的生理学特征关系密切[19]。通过扫描电镜对6种叶菜叶表面微结构进行观察发现(图3),杭白菜上表面较为平滑,粗糙度低(图3,A1),具有浅状的条纹突起,未观察到明显的气孔器。叶片下表面气孔呈褶皱状,纹路排列无规则,气孔器呈张开状态,但气孔较小(图3,A2),其波状起伏的沟壑结构有利于吸附颗粒物。苋菜叶片上表面粗糙且有凸起的纹路(图3,B1),下表面波状弯曲的褶皱状与细胞壁构陷成规则的褶皱状,且沟槽较深,但未能观察到气孔(图3,B2)。菠菜叶片上下表面微形态相似,上表面粗糙,略微凸起纹路(图3,C1),气孔开口小,几乎呈闭合状态,条状突起明显,但沟壑深度较浅且沟槽不密集;下表面沟槽交错与周边组织形成的沟槽较宽,气孔附近有不规则条状组织,气孔开口小(图3,C2)。生菜叶片上表面光滑,气孔呈细长条状,开口度较小(图3,D1),此种结构不利于吸附细颗粒物。下表面粗糙且有沟壑组织,气孔器开口大于叶片上表面(图3,D2),其光滑的叶表面导致其吸附颗粒物的能力较弱。青菜叶片上表面粗糙,凸起的纹路交错形成较大的沟槽。因此青菜易于吸附颗粒物(图3,E1)。青菜下表面分布大量的气孔器,但开口较小,且气孔周围沟槽较浅(图3,E2),这样的结构不利于吸附细颗粒物。叶用番薯叶片上表面粗糙,布满波状弯曲的密集褶皱,皱褶与细胞周壁下限构成不规则的沟槽图3,F1)。叶片下表面气孔开口较大,气孔周围密布褶皱,褶皱与细胞周壁形成密集的波折状组织(图3,F2),其复杂的微观结构有利于吸附不同粒径颗粒物。



A1~F1分别为杭白菜、苋菜、菠菜、生菜、青菜和叶用番薯叶片上表面;A2~F2分别为杭白菜、苋菜、菠菜、生菜、青菜和叶用番薯叶片下表面。

1 means the adaxial leaf.2 means the abaxial leaf.A:*Brassica chinensis* var. *oleifera*,B:*Amaranthus tricolor* L.,C:*Spinacia oleracea* L.,D:*Lactuca sativa* var. *crispa*,E:*Brassica chinensis* L.,F:*Ipomoea batatas.*

图3 6种叶菜叶片上下表面扫描电镜照片

Fig.3 Scanning electron micrographs of six leaves surface

2.5 叶片微形态与吸附不同粒径颗粒物的关系

进一步通过线性拟合可见,气孔长度、气孔宽度与$PM_{>10}$质量呈显著相关(图4),随着气孔长度和宽度的增大,$PM_{>10}$质量也随之增加。研究发现,更大的气孔开口尺寸有利于植物叶面滞尘[25],这与本研究结果一致。气孔长度、宽度、气孔长宽比与$PM_{2.5\sim10}$质量无显著线性关系(图5)。气孔长度与$PM_{0.2\sim2.5}$质量呈相关关系,气孔宽度与$PM_{0.2\sim2.5}$质量呈显著相关(图6),随着气孔宽度的增大,细颗粒物质量也随之增加。李春义等[8]研究发现,气孔宽度与PM、PM_{10}和$PM_{2.5}$吸附量呈显著正相关关系($P<0.05$),由于气孔宽

度越大，开合度也越大，因此有利于拦截颗粒物，且粒径较小的颗粒物部分进入气孔。此外，刘玲等[26]研究认为气孔口大属于气孔吸附主导型，这类植物叶面主要以吸附细颗粒为主。Schönherr等[27]通过研究得出气孔密集且开口较大的植物叶片能够滞留更多的$PM_{2.5}$。本研究中以叶用番薯的气孔宽度最大，达到14.55 μm，易使细颗粒物聚集于叶表面。而苋菜与生菜气孔宽度和长度较小，导致其吸附颗粒物的能力小于其他4种叶菜。

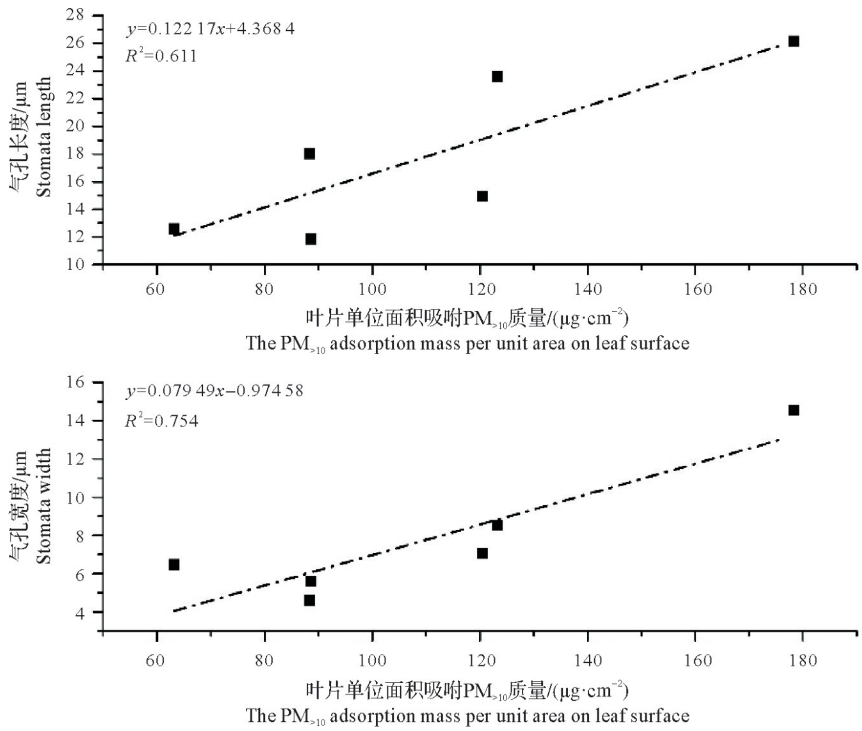


图4　叶片单位面积吸附$PM_{>10}$与气孔关系

Fig.4　The relationship between $PM_{>10}$ mass per unit area and stoma

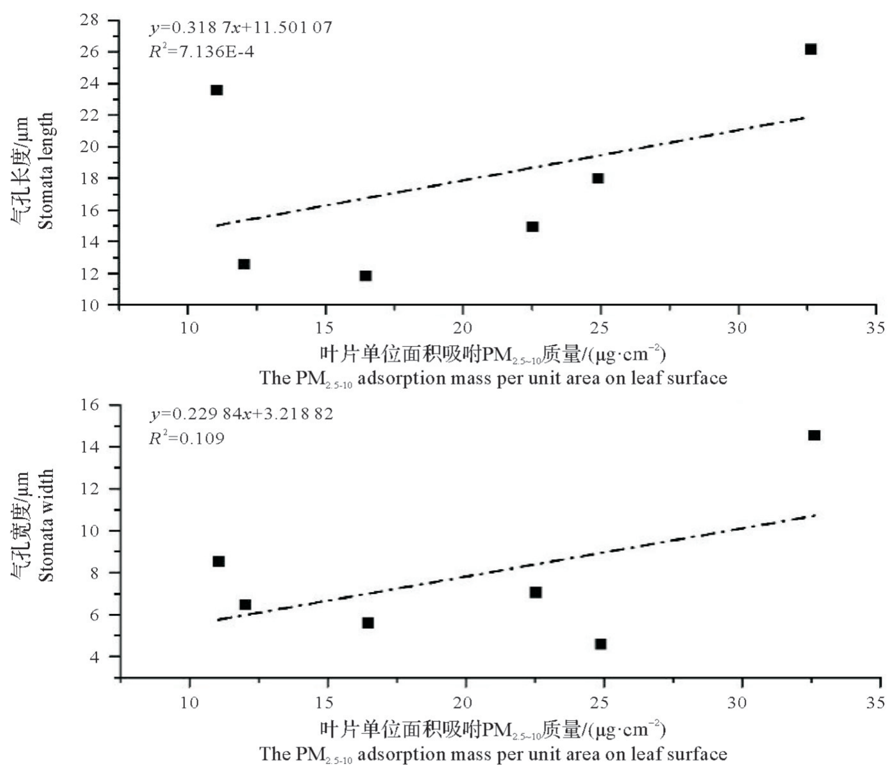
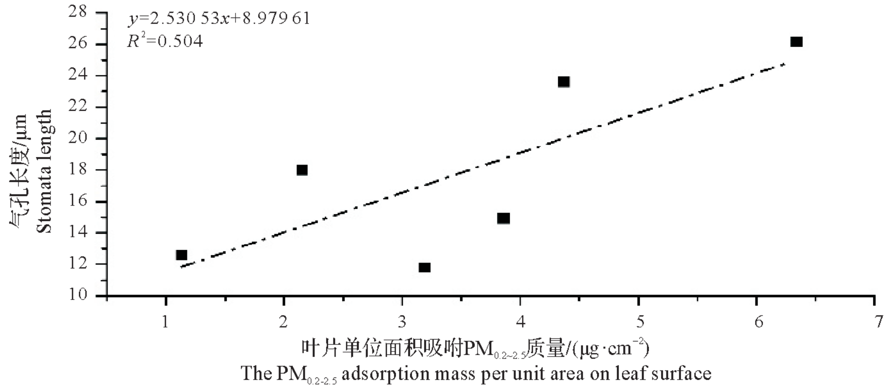


图5　叶片单位面积吸附$PM_{2.5\sim10}$与气孔关系

Fig.5　The relationship between $PM_{2.5\sim10}$ mass per unit area and stoma



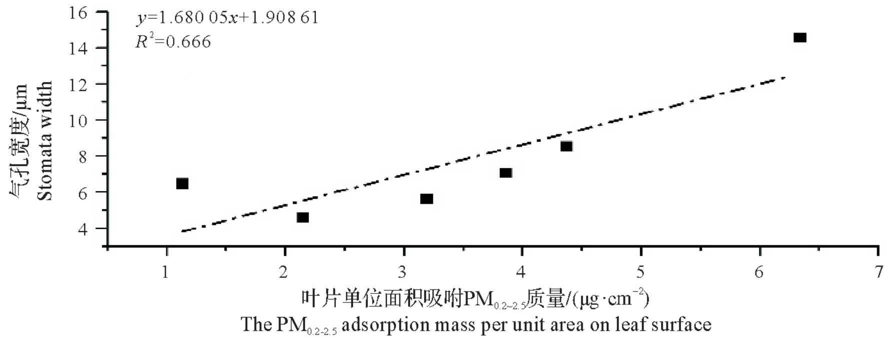


图 6　叶片单位面积吸附 $PM_{0.2\sim2.5}$ 与气孔关系

Fig.6　The relationship between $PM_{0.2\sim2.5}$ mass per unit area and stoma

表 1　$PM_{>10}$ 与气孔长度、宽度相关分析

Tab.1　The correlation analysis between $PM_{>10}$ and stoma length, width

	回归方程	R^2	F 值	Sig
气孔长度	y=0.122 17x+4.368 4	0.624	8.848	0.041<0.05
气孔宽度	y=0.079 49x−0.974 58	0.794	16.319	0.016<0.05

表 2　$PM_{2.5\sim10}$ 与气孔长度、宽度相关分析

Tab.2　The correlation analysis between $PM_{2.5\sim10}$ and stoma length, width

	回归方程	R^2	F 值	Sig
气孔长度	y=0.318 7x+11.501 07	7.136E−4	1.004	0.373>0.05
气孔宽度	y=0.229 84x+3.218 82	0.109	1.613	0.273>0.05

表 3　$PM_{0.2\sim2.5}$ 与气孔长度、宽度相关分析

Tab.3　The correlation analysis between $PM_{0.2\sim2.5}$ and stoma length, width

	回归方程	R^2	F 值	Sig
气孔长度	y=2.530 53x+8.979 61	0.504	6.085	0.069>0.05
气孔宽度	y=1.680 05x+1.908 61	0.666	10.956	0.03<0.05

*在 0.05 水平(双侧)上显著相关。

Significantly correlated at the 0.05 level(two sided).

3　结　论

本文在对 6 种叶菜吸附颗粒物特征的研究基础上,探讨了叶表微形态与吸附颗粒物能力的关系,得出以下结论:

(1)不同叶菜叶表面对总颗粒物的吸附能力存在差异,6 种叶菜叶片单位面积 TSP 吸附量由大到小依次为叶用番薯、青菜、菠菜、杭白菜、苋菜和生菜,以叶用番薯吸附总颗粒物的能力最强(22.62±4.15)$\mu g/cm^2$,生菜吸附能力最弱(6.46±1.22)$\mu g/cm^2$。

(2)通过比较叶菜对不同粒径颗粒物的吸附量可知,以叶用番薯对 $PM_{>10}$、$PM_{2.5\sim10}$ 及 $PM_{0.2\sim2.5}$ 的能力最强,以生菜吸附 $PM_{>10}$ 最弱,以杭白菜吸附 $PM_{2.5\sim10}$ 能力最弱,以苋菜吸附 $PM_{0.2\sim2.5}$ 能力最弱。

(3)叶菜叶片对不同粒径颗粒物的吸附特征与城市绿化植物一致,主要以吸附$PM_{>10}$为主,占总颗粒物质量的75.19%~88.42%,$PM_{2.5\sim10}$占总颗粒物质量的7.75%~22.93%,$PM_{0.2\sim2.5}$占总颗粒物质量的1.87%~4.19%。

(4)通过线性拟合可知,气孔长度、气孔宽度与$PM_{>10}$质量呈显著性关系,气孔长度与$PM_{0.2\sim2.5}$质量呈相关关系,气孔宽度与$PM_{0.2\sim2.5}$质量呈显著性关系。本研究中气孔宽度最大的叶用番薯(14.55 μm),其吸附颗粒物的能力最强。

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