Spent tea leaves: A new non-conventional and low-cost biosorbent for ethylene removal

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ABSTRACT

This characterization of the low-cost microsized spent tea leaf powder (MSTLP) and the effectiveness on its use as biosorbent in the removal of ethylene from a gaseous stream was investigated. Microprocessing treatment of used tea leaves significantly enhanced its ethylene removal capability. The effects of MSTLP dosage, initial ethylene concentration, and temperature on the adsorption of ethylene on MSTLP were evaluated. Moreover, the surface area/pore size distribution, functional group, and morphology of MSTLP samples were characterized. The kinetic adsorption data conformed well to a pseudo-second-order equation, and this adsorption was involved in intraparticle diffusion. The negative value of ΔG0 and the positive value of ΔS0 indicate that the adsorption of ethylene onto MSTLP was a spontaneous process. The adsorption capacity was found to increase with decreasing temperature and increasing MSTLP dosage. The maximum adsorption capacities varied from 0.68 to 6.93 mol/g at 25 °C based on the fits of Langmuir isotherm. MSTLP could be regenerated, and reused ten times for ethylene adsorption. The results show that a suitable choice of the microprocessing procedure for agriculture byproducts permits production of cheap biosorbent with high sorption capacity of ethylene.

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1. Introduction

Ethylene (C2H4) is a gaseous phytohormone, which can stimulate the ripening process of climacteric fruits and vegetables. Fruits and vegetables will gradually lose their freshness failing the control of the environmental concentration of ethylene. Moreover, ethylene can increase respiratory activity, activity of some enzymes, alteration of metabolism, seed germination, and growth before harvesting (Saltveit, 1999). The adverse effects of ethylene during postharvest include a reduced storage life of many fruits, vegetables, and decorative crops. These effects occur very rapidly even in the presence of very small amounts of excess ethylene after harvest, i.e., during shipping and storage. Consequently, an overripe state of the fruit is reached easily with a loss of its quality, and such fruits are then considered as unmarketable owing to the consequently reduced benefits of their shelf life (Alver, 2013). Thus, control of the ambient concentration of ethylene and removal of its excess quantities from an ethylene-sensitive environment of fresh products are both important to delay over-ripening and to extend postharvest storage life. Various conventional methods have been proposed to remove ethylene from the ethylene-sensitive environment, such as adsorption and oxidation processes. Chemical ethylene scrubbers are the most commonly used instruments to control the ethylene concentration during postharvest storage (Elsgaard, 1998). In the adsorption process, zeolites and carbon-based adsorbents can be used for ethylene removal (Wills and Warton, 2004; Keller et al., 2013). However, chemical scrubbers have a major drawback in that they are costly in terms of their maintenance and replacement of chemical agents (Reddy et al., 2012; Zhao et al., 2012). To lower operation costs, a bioscrubber was introduced in the last two decades for pollutant removal without regeneration of a chemical agent (Kim, 2006; Liu et al., 2006; Arantes et al., 2009; Fu et al., 2011; Kazmierczak et al., 2013; Soltani et al., 2013; Xiong et al., 2013; Yu et al., 2013; Zolgharnein et al., 2013; Chand et al., 2014). Development of new valuable adsorbent using environmental-friendly materials is most desirable.

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Because agriculture byproducts and wastes are rich in cellulose, hemicelluloses, and lignin, they are assumed to be potential adsorbents on account of their biodegradability, nontoxicity, and separation efficiency (Sharma and Bhattacharyya, 2004; Hossain et al., 2005; Babu and Gupta, 2008; Reddy et al., 2012; Zhao et al., 2012; Kazmierczak et al., 2013; Nowicki et al., 2013). Tea is the most important agricultural commodity in the world. During the preparation of a tea beverage or the manufacturing of instant tea and bottled tea drinks, raw tea leaves is contacted with hot water or steam. From these operations, a solid residue known as spent tea leaves (STL) waste is produced. STL have no commercial value and are usually discarded as solid waste. Recent increases in tea consumption around the world have led to the production of large amounts of tea waste that requires disposal (Cai et al., 2015). Moreover, the increasing awareness of the need for waste reduction and environmental protection has stimulated the search for possible methods of using this waste (Zuorro and Lavecchia, 2012).

2.2. Characterization of MSTLP

was kept in an airtight storage bag for further use in the adsorption and environmental protection has stimulated the search for possible methods of using this waste (Zuorro and Lavecchia, 2012). However, STL are a non-conventional and cost-effective adsorbent (Hossain et al., 2005). Recently, Weng et al. (2013) explored the application of STL powder as a biosorbent for the elimination of pollutants from aqueous solution. STL saturated with organic contaminants can be composted. The use of STL as a potential source of biosorbent for phytohormone removal is another promising. However no study has focused on the phytohormone removal using STL. To obtain further insight into the potential application of STL, we studied the adsorption behavior of ethylene on STL powder.

An attempt was made to use microsized STL powder (MSTLP) as a biosorbent for the removal of the plant hormone ethylene in postharvest. To the best of our knowledge, no such study has been conducted thus far, despite the importance of control of ambient ethylene concentration from the viewpoint of preserving the freshness of fruits and vegetables. We expected the micro-processing treatment of STL to result in an increase in the specific surface area with an increase in ethylene adsorption capacity. We then investigated the effectiveness of MSTLP as a biosorbent for the removal of ethylene from a gaseous stream on the basis of its kinetics, adsorption equilibrium prospects, and regeneration capacity.

2. Material and methods

2.1. Preparation of MSTLP

STL was collected from a beverage chain store in Taiwan. It was washed thoroughly several times with double-distilled water to remove dust remaining on the STL surface. Before pretreatment, STL was first dried at room temperature and then in an oven (80 °C) overnight. Dried STL, referred to as raw STL (RSTL), was then converted into fine STL powder (FSTLP) by grinding in a mechanical grinder and sieving through a 9-mesh sieve (2-mm mesh). FSTLP had an average particle size of about 830 μm. FSTLP was crushed into microsized powder via high-energy ball milling (PM100 Retsch, Germany) to obtain MSTLP. This MSTLP was kept in an airtight storage bag for further use in the adsorption study.

2.2. Characterization of MSTLP

The specific surface areas of RSTL, FSTLP, and MSTLP were measured by the Brunauer–Emmett–Teller nitrogen adsorption (BET-N₂) method using a QuantaSorb surface area analyzer (BET Micromeritics ASAP 2020, USA). Functional groups of MSTLP were characterized using a Fourier transform infrared spectrometer (FTIR Spectrum 100 PerkinElmer, USA) in the solid state with KBr.

Microstructural and morphological characterizations of FSTLP and MSTLP were conducted using a scanning electron microscope (SEM, S2700 Hitachi, Japan) at an acceleration voltage of 20 kV after gold sputtering under vacuum. The average particle size and size distribution were determined using a dynamic light scattering (DLS) analyzer (Nano-ZS, Malvern Instrument Ltd., Malvern, UK).

2.3. Kinetic and equilibrium adsorption experiments

Kinetics experiments of C₂H₄ adsorption onto MSTLP were performed to establish the effect of time on the adsorption process and to quantify the adsorption rate. Experiments were conducted with an initial C₂H₄ concentration of 2580 μmol/L and adsorbent dosage of 5 g. The effects of adsorbent dosage and ethylene concentration on the adsorption kinetics were determined by varying the absorbent dosage from 1 to 5 g and using different initial C₂H₄ concentrations (6–3350 μmol/L) at 25 °C. Ethylene was obtained in a compressed-gas cylinder. The typical experimental procedure was as follows. The desired amount of MSTLP was placed in a reactor, following which C₂H₄ was injected into the reactor. The rotation rate of the mixer (RM-2 Elmi, USA) was 50 rpm. When the reactor was rotating, the gas was withdrawn at designated time intervals. Temperature was controlled to isothermal conditions at 5, 15, 25, 35, and 45 °C by placing the entire assembly in an isothermal incubator (RIN-45 RISEN, Taiwan). The reactors were first placed in the incubator for 1 h prior to the experiment to establish thermal equilibrium. Samples were analyzed using a gas chromatograph (GC, PerkinElmer, Claurus 500, USA) equipped with a flame ionization detector (FID) and a thermal conductivity detector (TCD). The GC was equipped with an Elite Plot Q capillary column (Agilent Technologies) with a length of 30 m, film thickness of 0.25 μm, and internal diameter of 0.32 mm. Each run of the experiment was replicated, and the average values were used for data analysis. Blank tests without absorbent were run in parallel to avoid possible adsorption on the reactor. Isotherm experiments were performed to determine the maximum adsorption capacity and thermodynamic parameters. The experimental procedure in these experiments was the same as that described above. The amount of C₂H₄ adsorbed per unit mass of the absorbent (q, in μmol/g) was computed using the following expression:

\[
q = \frac{(C_0 - C_t)V}{m}.
\]

where \(C_0\) and \(C_t\) are the C₂H₄ concentrations in μmol/L before and after adsorption, respectively, for time \(t\); \(m\) (g) is the amount of biosorbent; and \(V\) is the volume (L) of the reactor.

2.4. Mathematical model

2.4.1. Kinetics of adsorption

The kinetic data were analyzed using the pseudo-second-order (PSO) model, expressed as

\[
\frac{dq}{dt} = k_2(q_e - q_t)^2
\]

where \(q_e\) and \(q_t\) denote the amounts of ethylene adsorbed on MSTLP (μmol/g) at equilibrium and at time \(t\) (min), respectively, and \(k_2\) is the PSO rate constant (g/μmol-min). After integration of the above equation and application of boundary conditions \(q_t = 0\) at \(t = 0\) and \(q_t = q_e\) at \(t = t\), the integrated form of the equation becomes
\[ \frac{1}{q_e - q_t} = \frac{1}{q_e} + k_t, \]  
which can also be written as,
\[ q_t = \frac{1}{k_2 q_e} + \frac{t}{q_e}, \]
or as
\[ \frac{t}{q_t} = \frac{1}{B} + \left(\frac{1}{q_e}\right) t, \]
in the linear form, where \( B = k_2 q_e^2 \) is the initial sorption rate as \( t \to 0 \).
If the PSO kinetics is applicable, the plot of \( t/q_t \) versus \( t \) will show a linear relationship, which allows computation of \( q_e, k, \) and \( B \) without having to know any parameter beforehand.

Temperature effects on the removal rate of ethylene were further investigated in detail with the application of the Arrhenius equation. The linear form of the Arrhenius equation is expressed as follows:
\[ \ln(k) = \ln(A) - \frac{E_a}{RT}, \]
where \( A \) is the pre-exponential factor, \( R \) is the universal gas constant, \( T \) is the absolute temperature, and \( E_a \) is the activation energy.

### 2.4.2. Adsorption isotherms

The Langmuir adsorption isotherm was used to describe the \( C_2H_4 \) adsorption:
\[ q_e = \frac{K_L q_{\text{max}}}{1 + K_L C_e}, \]
where \( q_e \) is the amount of \( C_2H_4 \) adsorbed at equilibrium, \( K_L \) is the Langmuir adsorption constant, \( C_e \) is the \( C_2H_4 \) concentration at equilibrium, and \( q_{\text{max}} \) is the maximum adsorption capacity. Equation (7) can be rearranged to,
\[ \frac{C_e}{q_e} = \frac{1}{K_L q_{\text{max}}} + \left(\frac{1}{q_{\text{max}}}\right) C_e \]

The plot of \( (C_e/q_e) \) versus \( C_e \) should give a straight line. The slope and intercept of this plot give the values of \( q_{\text{max}} \) and \( K_L \), respectively.

### 2.4.3. Thermodynamics of adsorption

Adsorption is usually an exothermic process, and as the temperature increases, the amount adsorbed at a given concentration decreases in accordance with Le Chatelier’s principle. The thermodynamic parameters for the adsorption of ethylene onto MSTLP were evaluated through a computation of the change in the Gibbs energy \( (\Delta G^0) \), entropy of adsorption \( (\Delta S^0) \), and enthalpy of adsorption \( (\Delta H^0) \) (Milonjic, 2007):
\[ \Delta G = \Delta H^0 - T \Delta S^0, \]
\[ \Delta G^0 = -RT \ln(K_L) \]
The values of \( \Delta H^0 \) and \( \Delta S^0 \) can be estimated from the following equation (Hema and Arivoli, 2008a,b):
\[ \ln(K_L) = \frac{\Delta H^0}{RT} + \frac{\Delta S^0}{R}. \]

### 2.5. Desorption and regeneration

For desorption and regeneration studies, MSTLP was first saturated with ethylene by placing 5 g of MSTLP at 25 °C in the reactor, and then, \( C_2H_4 \) was injected into the reactor (initial conc.: 560 μmol/L). MSTLP was collected in a 500-mL beaker after ethylene was completely adsorbed and then dried in an oven at 120 °C for 15 h. The MSTLP regeneration test was performed 10 times by following the same process.

### 3. Results and discussion

#### 3.1. Characterization of MSTLP

The DLS results indicated that the average particle size of MSTLP was 2.7 μm. The results of BET analysis confirmed that the RSTL sample did not contain any micropores and that the FSTLP sample had a relatively small number of micropores. Microprocessing treatment of STL powder resulted in a 10.6-fold increase in the micropore surface area compared to that of FSTLP. The micropore surface area and micropore volume of MSTLP were found to be 1.26 m²/g and 0.01 cm³/g, respectively.

Fig. 1(a) and (b) shows the surface morphologies of FSTLP and MSTLP, respectively. FSTLP did not have a sufficient number of pores. The microprocessing treatment of FSTLP appeared to have changed its surface characteristics and increased the volume of the pore space. Some particles were observed to have covered the pore surface of FSTLP, which resulted in a decrease in its surface area (Fig. 1). In contrast, the surface of MSTLP was found to contain heterogeneous-type pores. The number of these pores was sufficient for adsorbing ethylene. Consequently, the adsorption of ethylene on MSTLP was higher than that on RSTL and FSTLP.

FTIR spectroscopy was used to characterize the functional groups present on pure MSTLP and ethylene-adsorbed MSTLP. Fig. 2 shows the FTIR spectra of MSTLP before and after ethylene adsorption; these spectra reveal the presence of various functional groups on the surface of MSTLP. A broad peak at around 2925 cm⁻¹ confirms the presence of the –OH group. The peaks at 1618 cm⁻¹ indicate the presence of C=O bonds, and those at 1034 cm⁻¹ confirm the presence of C–O bonds. Because no significant changes occurred at the peak position before and after \( C_2H_4 \) adsorption, the chemical nature of the adsorbent remained the same even after \( C_2H_4 \) adsorption. It appears that \( C_2H_4 \) did not participate in the retention of the adsorbate with the main adsorbed state. The similarity of both the spectra along with almost the same peak intensity confirms the retention of the same type of adsorbent species in both the samples.

#### 3.2. Comparison of various treatment methods

Fig. 3(a) shows a comparison of the adsorption kinetics of ethylene on RSTL, FSTLP, and MSTLP. RSTL, which was not powdered, had negligible ethylene adsorption capacity. However, when it was powdered, the adsorption capacity increased sixfold. The microprocessing treatment of STL enhanced its ethylene adsorption capacity to up to 17 times the original capacity. The order of ethylene adsorption onto the considered adsorbents is as follows: RSTL < FSTLP < MSTLP. Smaller particles showed greater ethylene adsorption affinity, which was attributed to an increase in the surface area and pore volume. A linear relationship was observed between the amount of ethylene adsorbed and the surface area of the biosorbent. Larger surface areas with micropores in MSTLP are more favorable for \( C_2H_4 \) adsorption because of the availability of more surface active sites for adsorption.
3.3. Effect of biosorbent dosage

Fig. 3(b) shows the variation in the amount of C$_2$H$_4$ adsorbed at different MSTLP dosages. The adsorption increased from 5.0 to 19.7 μmol when the dosage of MSTLP was increased from 1 to 5 g within 7.5 h. An increase in the adsorbent dosage resulted in an increase in C$_2$H$_4$ removal efficiency, which is ascribed to the increase in the availability of the total number of surface active sites for adsorption. Fig. 3(b) also demonstrates a linear relationship between the amount of ethylene adsorbed and the surface area of MSTLP. As can be seen from the figure, on average, a surface area of 1 m$^2$ can adsorb 3.4 μmol of C$_2$H$_4$. It is concluded that the increase in adsorbent dosage clearly causes an increase in the C$_2$H$_4$ removal efficiency.

3.4. Adsorption kinetics

3.4.1. Effect of initial C$_2$H$_4$ concentration

Fig. 4 shows the effect of the initial ethylene concentration on its adsorbed amount. The amount of ethylene adsorbed was sensitive to its initial concentration. The uptake of ethylene by MSTLP was rapid within the first 40 min. After 40 min, the adsorption progressively decreased with time. At all initial concentrations, equilibrium was achieved at 100 min. Two phases were observed in the kinetic data: the first was fast adsorption and the second was progressive adsorption leading to equilibrium. In the first adsorption stage, around 85% ethylene was removed in all cases. The fast phase resulted mainly from the rapid attachment of ethylene to the active site of the biosorbent by surface mass transfer. The second phase of slow adsorption is normally considered as being attributed to diffusion into the interior pore space of MSTLP because most of the readily available sites were occupied.

The kinetic data were analyzed using a PSO model, as expressed in Eqs. (2)–(5). The fittings of the PSO model to the kinetic data are shown as solid lines in Fig. 4. Table 1 summarizes the amount of ethylene adsorbed at various initial concentrations and different temperatures and the corresponding fitting parameters of the PSO model. The high R$^2$ values indicate that the data can be described with the PSO model. It is evident from these results that the
adsorption rate is greatly affected by the initial ethylene concentration.

3.4.2. Effect of reaction temperature

Temperature plays a crucial role in ethylene adsorption. Fig. 5(a) shows the temperature dependence of the adsorption; the experimental data were found to be well fitted by the PSO model. The values of PSO constants \( q_e \), i.e., the equilibrium adsorption capacity, and \( k_2 \), i.e., the PSO rate constant, are also listed in Table 1. From this table, it is seen that the calculated and experimental \( q_e \) values are similar and the correlation coefficients are high (\( R^2 > 0.96 \)), confirming the applicability of the PSO model to the modeling of the kinetic adsorption of ethylene onto MSTLP. Both the calculated and the experimental values of \( q_e \) decreased with an increase in temperature. The experimental values of \( q_e \) were 1.74 \( \mu \)mol/g and 0.35 \( \mu \)mol/g at 5 °C and 45 °C, respectively. The rate constant increased from 0.070 g/mol-min to 0.101 g/mol-min as the temperature increased from 5 to 45 °C. Thus, it was confirmed that an increase in temperature results in an increase in the adsorption rate.

Fig. 5(b) shows the plot of \( \ln(k_2) \) versus \( 1/T \); the values of \( A_1 \) and \( E_a \) were determined from the slope of the plot. Normally, \( E_a \) value of a physical adsorption process is less than 4.0 kJ/mol because the bonding forces involved in physical adsorption are weak. The \( E_a \) value for chemical adsorption is usually higher than 4–6 kJ/mol, whereas a diffusion-controlled process has an \( E_a \) value lower than 42 kJ/mol (Wang et al., 2009). The obtained \( E_a \) value is 6.56 kJ/mol, which indicates the adsorption of ethylene that occurred during the diffusion control process (physical adsorption).

3.5. Adsorption isotherms

Fig. 6(a) shows that the magnitude of ethylene adsorption is proportional to temperature; the obtained results were fitted to the Langmuir isotherm given in Eq. (7). Table 2 lists the calculated Langmuir constants (i.e., \( q_{\text{max}} \) and \( K_L \)). The high correlation coefficients (i.e., \( R^2 > 0.92 \)), which confirm the equilibrium data, could be well represented by the Langmuir isotherm. The changes in the free energy (\( \Delta G_0 \)), enthalpy (\( \Delta H_0 \)), and entropy (\( \Delta S_0 \)) owing to the adsorption of ethylene onto MSTLP were calculated from the van’t Hoff plot (Fig. 6(b)) and are listed in Table 2. The negative value of \( \Delta H_0 (-4.01 \text{ kcal/mol}) \) indicates that the adsorption was exothermic in nature and that it was a diffusion-controlled process (Hema and Arivoli, 2008a,b.). Moreover, the small value of \( \Delta H_0 \) implies weak bonding between ethylene and the MSTLP surface. The negative value of \( \Delta G_0 \) and the positive value of \( \Delta S_0 (26.42 \text{ cal/K-mol}) \) indicate that the adsorption of ethylene onto MSTLP was a spontaneous process. The low value of \( \Delta S_0 \) may imply that no remarkable change in entropy occurred during the adsorption of ethylene onto MSTLP. The positive value of \( \Delta S_0 \) indicates that randomness increased at the gas–solid interface during adsorption. Normally, adsorption of gases causes a decrease in entropy owing to an orderly arrangement of the gas molecules on a surface. An increase in the \( \Delta G_0 \) values from −4.30 to −3.28 kcal/mol with a decrease in temperature from 45 to 5 °C indicated that the adsorption process was more favorable and spontaneous at low temperatures. MSTLP could become an alternative cost-effective adsorbent in bioscrubbers for ethylene removal.

<p>| Table 1 | Predicted constants of pseudo-second-order kinetic model for the adsorption of ( \text{C}_2\text{H}_4 ) onto MSTLP at various temperatures. |</p>
<table>
<thead>
<tr>
<th>Temp. (°C)</th>
<th>Experiment</th>
<th>Pseudo-second-order model</th>
<th>Activation energy</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( q_{\text{exp}} ) (( \mu )mol/g)</td>
<td>( q_e ) (( \mu )mol/g)</td>
<td>( k_2 ) g/mol min</td>
</tr>
<tr>
<td>5</td>
<td>1.74</td>
<td>1.80</td>
<td>0.070</td>
</tr>
<tr>
<td>15</td>
<td>1.47</td>
<td>1.48</td>
<td>0.075</td>
</tr>
<tr>
<td>25</td>
<td>1.12</td>
<td>1.18</td>
<td>0.082</td>
</tr>
<tr>
<td>35</td>
<td>0.69</td>
<td>0.70</td>
<td>0.092</td>
</tr>
<tr>
<td>45</td>
<td>0.35</td>
<td>0.40</td>
<td>0.101</td>
</tr>
</tbody>
</table>
3.6. Regeneration studies

MSTLP used once for ethylene adsorption can again be converted into a biosorbent material and can be used several times without any further treatment. In this study, desorption experiments showed that nearly 100% of ethylene could be removed simply by just heating MSTLP. Tea leaf powder can be recycled ten times by the same process. The experiment results showed that MSTLP could be used ten times for ethylene adsorption. They also showed that MSTLP can be restored without reducing its adsorption capacity. These results confirmed that the adsorption of ethylene onto MSTLP was a weak-adsorption-interaction process.

3.7. Comparison with the other adsorbents

Table 3 presents the comparative ethylene adsorption capacities of MSTLP and of some other economical adsorbents as obtained from a literature review (Wu et al., 1997; Wills and Warton, 2004; Kima et al., 2005; Liu et al., 2006; Albunia et al., 2008). Generally, zeolites and carbon-based materials are used as absorbents for the removal of ethylene. The adsorption capacities of zeolites as absorbents were reported by Kim et al. as being in the range of 0.7–1.3 μmol/g (Kima et al., 2005). Moreover, the ethylene removal capacity of clay minerals (~10 μmol/g) is greater than that of MSTLP (6.93 μmol/g) (Albunia et al., 2008). Although MSTLP has a lower ethylene removal capacity than activated carbon, MSTLP has advantages of being inexpensive, easily available, and eco-friendly, and having a high regeneration capacity. Therefore, MSTLP potentially has practical applicability as an economically feasible adsorbent for ethylene removal in the postharvest environment.

4. Conclusions

MSTLP can be used as an efficient, green, and cost-effective biosorbent for the removal of ethylene in the postharvest environment. The conversion of used tea leaves, which are easily available in huge amounts, to MSTLP did not require much energy, and MSTLP was confirmed to have high ethylene adsorption capacity. This biosorbent can be easily regenerated by washing and oven drying. The adsorption capacity of MSTLP increases with a decrease in temperature, increase in the initial ethylene concentration, and increase in its dosage. The adsorption of ethylene follows the PSO kinetics and is exothermic and spontaneous in nature.

### Table 2

Thermodynamic parameters for the adsorption of C2H4 onto MSTLP.

<table>
<thead>
<tr>
<th>Temp. (°C)</th>
<th>qmax (μmol/g)</th>
<th>K (l/mol)</th>
<th>R²</th>
<th>ΔG° (kcal/mol)</th>
<th>ΔH° (kcal/mol)</th>
<th>ΔS° (cal/K mol)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>15.01</td>
<td>377</td>
<td>0.96</td>
<td>–3.28</td>
<td>–4.01</td>
<td>26.24</td>
</tr>
<tr>
<td>15</td>
<td>10.22</td>
<td>487</td>
<td>0.95</td>
<td>–3.54</td>
<td>–3.81</td>
<td>–4.11</td>
</tr>
<tr>
<td>25</td>
<td>6.93</td>
<td>619</td>
<td>0.92</td>
<td>–3.81</td>
<td>–4.11</td>
<td>–4.30</td>
</tr>
<tr>
<td>35</td>
<td>4.34</td>
<td>820</td>
<td>0.97</td>
<td>–4.11</td>
<td>–4.30</td>
<td>–4.50</td>
</tr>
<tr>
<td>45</td>
<td>2.36</td>
<td>907</td>
<td>0.96</td>
<td>–4.30</td>
<td>–4.50</td>
<td>–4.70</td>
</tr>
</tbody>
</table>

Experimental conditions: [C2H4]i = 600 μmol/L, MSTLP = 5 g.

### Table 3

Comparison of adsorption capacities of various adsorbents for ethylene gas.

<table>
<thead>
<tr>
<th>Adsorbents</th>
<th>BET-SSA (m²/g)</th>
<th>Temp. (°C)</th>
<th>Adsorption capacity (qmax, μmol/g)</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biomass MSTLP</td>
<td>1.26</td>
<td>25</td>
<td>6.93</td>
<td>This study</td>
</tr>
<tr>
<td>Zeolite NaMOR18</td>
<td>320</td>
<td>30</td>
<td>1.3</td>
<td>Kima et al., 2005</td>
</tr>
<tr>
<td>Zeolite HMOR18</td>
<td>340</td>
<td>30</td>
<td>1.2</td>
<td>Kima et al., 2005</td>
</tr>
<tr>
<td>Zeolite HMOR240</td>
<td>340</td>
<td>30</td>
<td>0.7</td>
<td>Kima et al., 2005</td>
</tr>
<tr>
<td>Clay Minerals</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TiO2-pillared Saponite</td>
<td>368</td>
<td>20</td>
<td>10</td>
<td>Ooka et al., 2004</td>
</tr>
<tr>
<td>TiO2-pillared Montmorillonite</td>
<td>301</td>
<td>20</td>
<td>15</td>
<td>Ooka et al., 2004</td>
</tr>
<tr>
<td>TiO2-pillared Fluorine mica</td>
<td>402</td>
<td>20</td>
<td>10</td>
<td>Ooka et al., 2004</td>
</tr>
<tr>
<td>Activated Carbon</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Carbon nano balls</td>
<td>1431</td>
<td>30</td>
<td>–7 – 11</td>
<td>Liu et al., 2006</td>
</tr>
<tr>
<td>Pd/CNB</td>
<td>827</td>
<td>30</td>
<td>–14 – 71</td>
<td>Liu et al., 2006</td>
</tr>
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<td>Activated carbon</td>
<td>1120</td>
<td>30</td>
<td>–11 – 78</td>
<td>Liu et al., 2006</td>
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<td>1109</td>
<td>30</td>
<td>–7 – 71</td>
<td>Liu et al., 2006</td>
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Acknowledgments

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