Soil remediation: humic acids as natural surfactants in the washings of highly contaminated soils

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Abstract

Soil remediation of the highly contaminated site around the former chemical plant of ACNA (near Savona) in Northern Italy is a top priority in Italy. The aim of the present work was to contribute in finding innovative and environmental-friendly technology to remediate soils from the ACNA contaminated site. Two soils sampled from the ACNA site (A and B), differing in texture and amount and type of organic contaminants, were subjected to soil washings by comparing the removal efficiency of water, two synthetic surfactants, sodium dodecylsulphate (SDS) and Triton X-100 (TX100), and a solution of a natural surfactant, a humic acid (HA) at its critical micelle concentration (CMC). The extraction of pollutants by sonication and soxhlet was conducted before and after the soil washings. Soil A was richer in polycyclic aromatic hydrocarbons, whereas soil B had a larger content of thiophenes. Sonication resulted more analytically efficient in the fine-textured soil B. The coarse-textured soil A was extracted with a general equal efficiency also by soxhlet. Clean-up by water was unable to exhaustively remove contaminants from the two soils, whereas all the organic surfactants revealed very similar efficiencies (up to 90\%) in the removal of the contaminants from the soils. Hence, the use of solutions of natural HAs appears as a better choice for soil washings of highly polluted soils due to their additional capacity to promote microbial activity, in contrast to synthetic surfactants, for a further natural attenuation in washed soils.

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1. Introduction

Soil is a complex matrix permanently interacting with other environmental compartments such as waters and air (Schwarzenbach et al., 2003) and thus its pollution can directly propagate contamination to surface and ground waters, and air (Fent, 2003). Soil pollution may be due to industrial accidents (spills, leaks, and leaking underground storage tanks) (Ballarin-Denti et al., 1999; Lee et al., 2002; Kiem et al., 2003) and anthropogenic activities (forest and agricultural fires, fossil fuel combustions) (Simcik et al., 1999; Venkataraman et al., 2002), and represents a long-term source of environmental contamination. Weak interactions bind soil constituents to contaminants (Piccolo et al., 1996; Chin et al., 1997; Zhou and Rowland, 1997; Kopinke et al., 2000; Peuravuori, 2001; Peuravuori et al., 2002; Paaso
et al., 2002) which, once displaced from the weak bonds, may be again released in the environmental compartments (Gaboriau and Saada, 2001; Huang et al., 2003; Ockenden et al., 2003) and affect the human food-chain (Ballarin-Denti et al., 1999; Mackay and Fraser, 2000; Borgà et al., 2001).

New soil remediation technologies emphasizes the transformation and detoxification of pollutants. For example, bioremediation enables permanent elimination of pollutants by in situ remediation at low cost. However, bioremediation is limited by the correct selection of active microbes, the appropriate soil conditions for microbial activity, recalcitrance of pollutants to biodegradation, and formation of metabolites which may be more toxic than the parent contaminant (Boopathy, 2000).

Among other techniques, soil washing may be a valid and relatively inexpensive alternative in soil remediation (Kuhlman and Greenfield, 1999). It is based on the desorption of pollutants from contaminated soils through the action of simple water (Griffiths, 1995), or organic surfactants (Deshpande et al., 1999; Chu and Chan, 2003) which may be non-ionic (Garon et al., 2002; Mata-Sandoval et al., 2002) or anionic (Chun et al., 2002). The liquid phases containing the desorbed pollutants are then disposed or subjected to further chemical or biochemical treatments for complete detoxification (Mann, 1999).

Different classes of surfactants are employed for soil washing depending on the nature of contaminants to be removed. For example, pesticides are removed by non-ionic surfactants such as Triton X-100, and bio-surfactants like the rhamnolipids (Noordman et al., 2000; Mata-Sandoval et al., 2002). Polycyclic aromatic hydrocarbons (PAH) can be washed away by alkylphenol ethoxylate (Garon et al., 2002), hydroxypropyl-β-cyclodextrins (Cuypers et al., 2002), and other anionic surfactants such as sodium dodecylbenzene sulphonate, monoalkylated disulphonated diphenyl oxide, and dialkylated disulphonated diphenyl oxide (Chun et al., 2002). In general, water-soluble surfactants may disperse solids and liquids immiscible in water, while surfactants forming microemulsion solubilize hydrocarbons, and oil-soluble surfactants facilitate water recycling (Kuhlman and Greenfield, 1999). However, the use of surfactants in cleaning-up contaminated sites may be limited by soil texture and their intrinsic biological toxicity. Soils with large content of fine-sized textural particles (silt and clay) reduce considerably washing efficiency of surfactants (Kuhlman and Greenfield, 1999; Lee et al., 2002). The reported toxicity of surfactants on several soil microbial cells may prevent further biodegradation of pollutants and balanced biological activity in the washed soils (Sandbacka et al., 2000).

Humic substances (HAs), naturally occurring surfactants, begin to be recognized as a possible aid in soil bioremediation techniques. The bioavailability of polychlorinated biphenyls (Fava and Piccolo, 2002), and PAH (Holman et al., 2002) appeared to be increased by addition of exogenous humic substances to contaminated soils. Furthermore, the surfactant activity of HAs was found to reduce sorption of organic contaminants on spiked soils, thereby enabling desorption-remediation of PAH (Janzen et al., 1996; Chefetz et al., 2000; Conte et al., 2001; Holman et al., 2002), dioxins (Kim and Lee, 2002), and heavy metals (Weng et al., 2002; Halim et al., 2003). However, no studies have been so far reported on the application of HAs as surfactants in the soil washing of a real and highly contaminated site.

The aim of this work was to compare the efficiency of a humic acid (HA) with that of common surfactants (sodium dodecylsulphate, and Triton X-100) and water in the washing of two highly polluted soils sampled in the contaminated industrial area of a chemical plant. The soils were different in texture and composition of pollutants. One was rich in PAH, whereas the other had a high content of thiophenes. Moreover, the efficiency of two extracting procedures (Soxhlet and sonication) was also compared in order to suggest the best analytical procedure for the determination of the pollutants in the soils.

2. Materials and methods

2.1. The contaminated site

The industrial area of Cengio (near Savona) in Northern Italy is extremely polluted due to irregular disposal of contaminants on surface and lower soil horizons since 1882, when SIPE (Società Italiana Prodotti Esplodenti) began production of explosives. Later, SIPE became ACNA (Aziende Chimiche Nazionali Associate) that produced phenol, sulphuric acid, nitric acid and several other industrial organic intermediates. In 1939, ACNA additionally manufactured a range of colouring organic compounds (more information at: http://www.bonificare.it/). The serious environmental contamination (soils and waters) around the ACNA site determined in 1999 its inclusion in the list of national priorities for environmental reclamation and fostered a number of activities among which a scientific research on soil remediation led by the Interuniversity Consortium ‘Chemistry for the Environment’ (INCA, Venice, Italy; http://helios.unive.it/inca).

2.2. Soils

Two different soil samples (A and B) were sampled in the ACNA site. After air-drying, the soils were first 2.00 mm sieved, and, then, analysed for their texture and content of carbon and nitrogen (Fisons EA 1108 Elemental Analyzer). The values are reported in Table 1.
Table 1
Characteristics of soil A and B from the contaminated ACNA site at Cengio

<table>
<thead>
<tr>
<th></th>
<th>Soil A</th>
<th>Soil B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coarse sand (%)</td>
<td>21.2±0.6</td>
<td>12.8±0.4</td>
</tr>
<tr>
<td>Fine sand (%)</td>
<td>35.6±0.8</td>
<td>38.8±0.5</td>
</tr>
<tr>
<td>Silt (%)</td>
<td>39.6±0.5</td>
<td>43.6±0.7</td>
</tr>
<tr>
<td>Clay (%)</td>
<td>3.6±0.2</td>
<td>4.8±0.3</td>
</tr>
<tr>
<td>Carbon (%)</td>
<td>2.8±0.1</td>
<td>2.7±0.2</td>
</tr>
<tr>
<td>Nitrogen (%)</td>
<td>1.2±0.1</td>
<td>0.15±0.02</td>
</tr>
</tbody>
</table>

2.3. Reagents for soil washings

Solutions used for soil washings were: 1. MilliQ-grade water; 2. 4% (w/v) sodium dodecyl sulphate (SDS); 3. 4% (v/v) Triton X-100 (TX100) solutions; 4. 10 mg/l humic acid (HA). The latter is reported to be the critical micelle concentration of HAs (Guetzloff and Rice, 1999). SDS and Triton were obtained from Sigma® (Milano, Italy) and used without further purification. HA was isolated from a North Dakota Leonardite (Mammoth, Chem. Co., Houston, Texas), and purified as reported elsewhere (Conte and Piccolo, 1999). The HA was then suspended in distilled water and titrated to pH 7 by an automatic titrator (VIT 909 Videotitrator, Copenhagen) with a 0.1 M NaOH solution under N2 stream. The resulting sodium-humate was then filtered through a Millipore 0.45 µ and freeze-dried.

2.4. Soil washing

Soils (10 g) were suspended in 100 mL of each soil washing solution, and shaken for 24 h in a rotary shaker at 10 rpm. All suspensions were centrifuged in glass tubes at 10,000 rpm for 10 minutes in order to separate solid residues from washing solutions. The solid residues were dried at 40 °C and subjected to either ultrasonic or Soxhlet extraction.

2.5. Ultrasonic extraction

Each soil sample (10 g) either before or after the washing was suspended in 100 mL of an acetone/n-hexane (1:1) mixture, and sonicated with a Misonix XL2020 sonicator. A power of 55 Watt was applied for 12 minutes to the soil suspensions to obtain a total energy of 39.6 kJ. After sonication, the suspension was filtered through Whatman 40 paper filters, in order to separate the residue from the extract.

2.6. Soxhlet extraction

Each soil sample (10 g) either before or after the washing was weighed in Soxhlet filters, and extracted under reflux with 100 mL of an acetone/n-hexane (1:1) mixture in a Soxhlet equipment for 48 hours (Dean, 1999). According to the EPA SW 3630 B method, the acidic organic contaminants (such as organic acids and phenols) were removed from the extract by a liquid-liquid extraction with NaOH at pH 11. The organic phase was treated with Na2SO4 for the removal of residual water, and filtered through a Whatman 40 filter.

2.7. Sample pre-treatment

After filtration, the organic extracts coming from either sonication or Soxhlet, were first dried in a rotovaporator at 40 °C, and re-dissolved in 5 mL of CH2Cl2. 1 mL of the CH2Cl2 solution was purified by solid phase extraction (SPE) through elution in Bond-Elut C-18 cartridges (500 mg/3 mL from Varian) with 30 mL of n-hexane, according to EPA SW 8270 B method. The eluted n-hexane fraction was dried in a rotovaporator at 40 °C and re-dissolved in 1mL of CH2Cl2 and 1 mL of a 100 µg/mL octafluoronaphtalene solution in CH2Cl2, used as internal standard. The concentration of contaminants identified by GC-MS was then relative to that of octafluoronaphtalene.

2.8. GC-MS analysis

A Perkin-Elmer Autosystem™ XL gas-chromatograph, equipped with a Programmed-Temperature Split/Splitless injector with programmable pneumatic control kept at a constant temperature of 250 °C, a Restek RtX®-5MS capillary column (5% diphenyl-95% dimethylpolysiloxane, length 30 m, 0.25 mm ID, and 0.25 µm df), and a Perkin-Elmer TurboMass Gold mass-spectrometer, was used for qualitative and quantitative analysis of contaminants extracted from the original soils and their residues after the washings. The conditions used for GC analyses were the following: 1. initial temperature of 40 °C for 5 minutes; 2. to 250 °C at a 3 °C/min rate; 3. isothermal for 20 minutes. The total GC run time was 95 minutes. Helium was the carrier gas at 1.5 mL/min with a split-flow of 30mL/min. The inlet-line temperature of the GC-MS system was set at 280 °C, while that of the MS source at 180 °C. A solvent delay time of 5 minutes was applied before acquisition of the mass spectra to prevent filament injuries. Low and high m/z limits of the mass spectrometer were 50, and 400 amu, respectively. A NIST mass spectral library version 1.7 was used for peak identification.

2.9. Data treatment

Soxhlet and sonication extractions were performed in triplicate for each soil before and after soil washings. Each organic extract was analysed in duplicate by GC-MS analysis. Quantitative results by GC-MS
analyses were weight-averaged to provide experimental error.

3. Results and discussion

3.1. Effect of soil texture on contaminants extractability

Soxhlet and sonication are the most common liquid-solid extractive procedures used to obtain pollutants from soil samples (Dean, 1999). The former is a heat-requiring method, whereas sonication is based on the ultrasonic shaking of solid suspensions (Martens et al., 2002). Both methods remove semivolatile, and non-volatile organics from soils (US EPA methods 3540, and 3550). However, the removing efficiency of both methods may be strongly affected by soil characteristics and especially by soil texture (Jastrow, 1996; Pefferkorn, 1997). It is widely accepted that a fine-sized texture in soil is a main factor for the hydrophobic adsorption of organic matter on the surface of fine colloidal soil particles, thereby favouring the associations of micro-into macro-aggregates (Jastrow, 1996; Pefferkorn, 1997; Piccolo and Mbagwu, 1999). Concomitantly, the organic material trapped into the macroaggregates is physically protected from biodegradation and becomes hardly extractable by common extraction procedures, unless the soil macroaggregates are disrupted by applying either mechanical or sonication energy (Pefferkorn, 1997; Watts et al., 2000; Mulder et al., 2001; Plante and McGill, 2002). Conversely, coarse-sized soil particles are less prone to form larger soil aggregates mediated by organic matter (Kemper and Rosenau, 1986). Thus, organic compounds are located only on the surface of the coarse-sized fractions and result removable with the same efficiency by both soxhlet and sonication (Pefferkorn, 1997; Watts et al., 2000; Mulder et al., 2001).

For the two ACNA soils, the texture of sample A resulted larger in coarse-sized particles, whereas that of soil B was higher in fine-sand, silt and clay (Table 1). Concomitantly, the two soils resulted different in the amount of organic contaminants that could be extracted by either soxhlet or sonication (Table 2). Soil A was richer in polycyclic aromatic hydrocarbons (PAH), and monoaromatic halogenated and nitrogenated compounds and soil B had a larger content of thiophenes, sulphones, and biphenyls (Table 2). However, the total amount of respective contaminants extracted from soil A by soxhlet and sonication was not significantly different, whereas that of soil B was more exhaustively extracted by sonication (Table 2).

This different efficiency of extractions methods between soil A and B may be attributed to their different texture. The lower aggregate stability conferred to soil A by its larger content of coarse-sized fractions allowed a similar availability to both soxhlet and sonication extractions of organic compounds adsorbed on the outer surfaces of gross particles, thereby resulting in similar extracting efficiencies (Table 2). Conversely, in the fine-textured soil B, organic pollutants are adsorbed on the surfaces of fine particles contained in more structurally stable macroaggregates. Hence, the soxhlet extraction, based simply on temperature, could only wash away the fraction of contaminants mainly present on the surfaces of macroaggregates, whereas ultrasonic vibrations, by exerting a disaggregation energy on the macroaggregates (Babic et al., 1998; Martens et al., 2002), could also exposes to solubilization the pollutants adsorbed on the surfaces of the inner fine particles. For this reason, the amount of pollutants extracted by sonication from soil B resulted larger than that obtained by soxhlet (Table 2). An exception were the thiophenes that were obtained from soil B in equal amount both by soxhlet and sonication. This suggests that thiophenes were preferentially adsorbed mainly on the external surface of the soil aggregates, thereby being equally dissolved by solvent both in soxhlet and sonication.

3.2. Soil washings

The washing with just water was found not to efficiently remove pollutants from soil A (Fig. 1). In fact, the totality of pollutants obtained from soil A, both by soxhlet and sonication after washing with Milli-Q grade water, was only slightly lower than that recovered

<table>
<thead>
<tr>
<th>Contaminants</th>
<th>Soxhlet</th>
<th>Sonication</th>
<th>Soxhlet</th>
<th>Sonication</th>
</tr>
</thead>
<tbody>
<tr>
<td>PAH</td>
<td>4562±445</td>
<td>3792±130</td>
<td>986±129</td>
<td>1337±152</td>
</tr>
<tr>
<td>Monoaromatic halogenated and nitrogenated compounds</td>
<td>407±22</td>
<td>426±19</td>
<td>97±3</td>
<td>222±14</td>
</tr>
<tr>
<td>Thiophenes</td>
<td>37±4</td>
<td>28±2</td>
<td>2337±98</td>
<td>2815±344</td>
</tr>
<tr>
<td>Sulphones</td>
<td>211±27</td>
<td>227±10</td>
<td>243±12</td>
<td>360±41</td>
</tr>
<tr>
<td>Biphenyls</td>
<td>108±16</td>
<td>95±7</td>
<td>16±1</td>
<td>152±7</td>
</tr>
<tr>
<td>Other</td>
<td>78±6</td>
<td>96±6</td>
<td>31±10</td>
<td>47±5</td>
</tr>
</tbody>
</table>

Table 2 Amount (mg kg$^{-1}$) of specific contaminants extracted from soil A and soil B by both soxhlet and sonication
from the unwashed soil. Washing with water appeared more efficient in removing pollutants from soil B, especially when sonication was used for extraction procedure. This may be attributed in this fine-textured soil to a process of soil particle aggregation in water (Oades and Waters, 1991; Christensen, 1992; Puget et al., 2000) that limits pollutant solubilization by soxhlet.

Synthetic surfactants are reported to remove organic pollutants from contaminated soils by a mechanism involving repartition of pollutants into the surfactant micellar phases formed in water. However, this process would take place only when the surfactant solution reaches the surfaces of soil particles and the pollutants may be desorbed into the micellar phases (Noordman et al., 2000; Chun et al., 2002; Cuypers et al., 2002; Mata-Sandoval et al., 2002).

The soil washings conducted in this work by either synthetic (SDS and TX100) or natural surfactants (HA) were more efficient than water in removing significant amounts of pollutants from the highly contaminated soils (Fig. 1). In general, the synthetic surfactants used here were able to reduce the content of contaminants from the two soils from 80 to more than 90% and confirmed previous literature findings (Chefetz et al., 2000; Holman et al., 2002; Kim and Lee, 2002). This work also indicates for the first time that a natural non-toxic surfactant such as humic acid removes similar amounts of contaminants from a polluted soil as synthetic surfactants (Fig. 1).

Soil washing (SW) may affect soil structural hierarchy by redistributing the size of aggregate particles (Kemper and Rosenau, 1986). No significant difference was observed in the amount of PAHs, biphenyls, hydrophilic halogenated, and nitrogenated compounds, thiophenes, and sulphones obtained by soxhlet and sonication after SW of soil A with H2O (Table 3). Hence, the predominantly coarse texture of soil A did not produce any further particle aggregation in water that affects the removal of contaminants. The finer texture of soil B, instead, and the consequent tendency of soil particles to create aggregation, may be the reason for the larger amount of pollutants removed by sonication than by soxhlet (Table 4).

The use of either synthetic or natural surfactants in SW techniques may also have the effect of increasing soil structural stability due to the aggregating action that the hydrophobicity of surfactants may exert on the solid soil particles (Piccolo and Mbagwu, 1999). This may in turn affect the solubilization of contaminants during the determination procedures depending on the specific structure of pollutants.

A change in soil aggregation after soil washings may explain the results on the removal of specific pollutants.
Table 4
Amount (mg kg\(^{-1}\)) of pollutants extracted from soil B by both soxhlet and sonication after soil washing (SW) with H\(_2\)O, SDS, TX100, and HA

<table>
<thead>
<tr>
<th>Pollutants</th>
<th>SW-H(_2)O</th>
<th>SW-SDS</th>
<th>SW-TX100</th>
<th>SW-HA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>soxhlet</td>
<td>sonication</td>
<td>soxhlet</td>
<td>sonication</td>
</tr>
<tr>
<td>PAH</td>
<td>419 ± 5</td>
<td>1340 ± 20</td>
<td>338 ± 29</td>
<td>496 ± 43</td>
</tr>
<tr>
<td>Monoaromatic halogenated and halogenated compounds</td>
<td>67 ± 3</td>
<td>102 ± 4</td>
<td>54 ± 4</td>
<td>44 ± 6</td>
</tr>
<tr>
<td>Thiophenes</td>
<td>421 ± 9</td>
<td>563 ± 50</td>
<td>233 ± 22</td>
<td>282 ± 20</td>
</tr>
<tr>
<td>Sulphones</td>
<td>35 ± 1</td>
<td>71 ± 2</td>
<td>27 ± 1</td>
<td>71 ± 7</td>
</tr>
<tr>
<td>Biphenyls</td>
<td>11 ± 1</td>
<td>16 ± 1</td>
<td>9 ± 1</td>
<td>8 ± 1</td>
</tr>
<tr>
<td>Other</td>
<td>15 ± 1</td>
<td>14 ± 1</td>
<td>17 ± 1</td>
<td>15 ± 3</td>
</tr>
</tbody>
</table>

For soil A, after washing with SDS, the PAHs were subsequently more efficiently removed by sonication than by soxhlet (Table 3). Conversely, soxhlet allowed to obtain larger amounts of thiophenes, biphenyls, and monoaromatic nitrogenated and halogenated compounds (Table 3). After soil washing with TX100, sonication provided again larger amounts of hydrophobic PAHs and sulphones, whereas soxhlet appeared more efficient in obtaining thiophenes, and biphenyls (Table 3). These findings may be attributed to a variation in the aggregation of soil particles after treatment with surfactants and a consequent different distribution of pollutants in either inner or outer surfaces of new soil aggregates.

Also in the case of SW with HA, the treatment with this natural organic matter may have produced an alteration in aggregate distribution of soil A and consequent solubilization of different contaminants. However, in contrast to SDS and TX100, washing of soil A with HA was able to remove a significantly similar and large amount of PAHs by either soxhlet or sonication (Table 3). This may be attributed to the heterogeneity of the HA micellar phase and, hence, its capacity to incorporate with equal efficiency PAHs of different structures (Fava and Piccolo, 2002). Nevertheless, sonication removed more monoaromatic nitrogenated and halogenated compounds, and biphenyls than soxhlet, whereas the latter technique was more efficient in obtaining thiophenes (Table 3).

More than in soil A, alteration of soil aggregation in the finer-textured soil B due to washings appears to be the explanation of the removal of specific pollutants. Except for the SW in TX100, all other washings determined a subsequent removal of larger quantities of PAHs by sonication (Table 4). Sulphones, the larger contaminant in soil B (Table 2), were significantly removed in larger amounts by sonication than by soxhlet after SW with all solutions (Table 4). With few exceptions, the rest of specific contaminants found in soil B were more quantitatively removed by sonication after all SW procedures. This general more efficient extracting action of sonication for soil B after the SW in the different solution is parallel to that shown for the unwashed soil. Again, this is to be attributed to a larger structural stability of this soil whose interparticle association energy is overcome by application of sonication, thereby allowing a solubilization of specific pollutants impossible to reach by a simple soxhlet extraction.

4. Conclusions

This work has confirmed that water cannot be recommended for an efficient removal of pollutants from a contaminated soil and that organic surfactants should be relied upon in soil washing procedures. However, synthetic surfactants such as SDS, and TX100 which are efficient in soil washings may become a further environmental problem because of their biological toxicity. We have shown here that a natural surfactant such as a humic acid solution can be used in washings of a contaminated soil with the same efficiency as that of synthetic surfactants. The importance to promote the use of environmentally-safe humic substances in the remediation of heavily contaminated soils should be self-evident. Humic substances can even improve biomass activity on washed soils and contribute to a further natural attenuation once the soil are disposed after an ex situ remediation process (Fava and Piccolo, 2002; Marschner and Kalbitz, 2003). Moreover, the fraction of humic substances remaining in soil may play a favourable action in plant growth and thus assist in the full recuperation of the treated soils (Nardi et al., 2002).

Our findings have also indicated that soil texture is an important parameter to take into account to select the most appropriate analytical technique to remove and determine soil contaminants. We found that contaminants are more quantitatively removed by sonication rather than by soxhlet when a soil is characterized by a fine texture, whereas both soxhlet and sonication give equivalent results in more coarse-textured soils. However, since sonication is faster than soxhlet (in our experimental work it took only 12 minutes against 48 hours needed for soxhlet) the use of sonication should be recommended as a standard procedure for all kind of soils. The disadvantage of sonication, a reported degradation of aromatic organic pollutants (Goskonda
et al., 2002), is reasonably balanced by its more quantitative removal efficiency.

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References


