

## Chapter 2

# Solid Waste Conversion and Dynamic Multi-objective Optimization

**Abstract** A systemic study of the metabolic process of solid waste and the law of conversion and environmental effects of major pollutants will facilitate the solution to solid waste pollution, recycling pathways and multi-objective optimization strategies. Focusing on solid waste, this chapter probes into the law of material conversion, builds a metabolic dynamics model for typical pollutants integrating different disposal patterns, and reveals the metabolism mechanisms, migration pathways and major influencing factors in solid waste treatment and disposal. A mechanism of management towards effective environmental and economic trade-offs is formed, covering optimization, validation, and feedback.

**Keywords** Solid waste • Material transformation • Dynamics model • Metabolism mechanisms

## 2.1 Overview

Solid waste consists of electronic waste, construction waste and medical waste, as well as organic waste, including garbage, sludge, food wastes, straw and manure. It contains large amounts of toxic and hazardous substances that threaten the human environment. A systemic study of the metabolic process of solid waste and the law of conversion and environmental effects of major pollutants will facilitate the solution to solid waste pollution, recycling pathways and multi-objective optimization strategies. Furthermore, this will mitigate the negative impact of solid waste on the environment, improve the ecological environment, and lay an important foundation for developing the venous industry. Focusing on solid waste, this chapter probes into the law of material conversion, builds a metabolic dynamics model for typical pollutants integrating different disposal patterns, and reveals the metabolism mechanisms, migration pathways and major influencing factors in solid waste treatment and disposal. Furthermore, a dynamic multi-objective optimization model reflecting the Chinese characteristics is introduced, which rests on

multi-objective planning framework, pollution loss theory, and uncertainty analysis. A mechanism of management towards effective environmental and economic trade-offs is formed, covering optimization, validation, and feedback.

## **2.2 Law of Solid Waste Conversion and the Environmental Effects**

### ***2.2.1 Humification of Organic Waste***

#### **2.2.1.1 Changes in Physical and Chemical Properties and Biological Booster Doses**

In the humification process, compost temperature change, within a certain range, is positively correlated with growth and reproduction of microorganisms, including heating, thermophilic and cooling (mature period) phases. Studies have shown that, in general, humification occurs in the late thermophilic phase. In aerobic humification process, organic macromolecules are degraded by microbes into small molecules and finally converted to  $\text{CO}_2$  and  $\text{H}_2\text{O}$ . The  $\text{NH}_3$  volatilization first increases slowly and then gradually decreases in the compost heating and thermophilic phases before achieving relative stability in the mature period. The study found the oxygen consumption rate and  $\text{CO}_2$  release rate reach the peak in the thermophilic phase. Microbial inoculation can suppress the  $\text{NH}_3$  volatilization and accelerate the humification process by significantly increasing the number of microbes and efficiency of organic matter decomposition, as well as oxygen consumption rate and  $\text{CO}_2$  release rate in the thermophilic phase.

#### **2.2.1.2 Dynamic Changes of Organic Matter**

##### **(1) Total organic carbon (TOC)**

Humification is generally accompanied by organic matter mineralization, and the two are a unity of opposites. In this process, a part of organic carbon is mineralized into  $\text{CO}_2$  and  $\text{H}_2\text{O}$ , releasing energy to support microbial growth. Organic carbon content shows a decreasing trend, with notable decline in the heating, thermophilic phases and moderate decline in the mature period. Hence, humification is generally considered dominant in the middle and late phases. The decomposition rate of organic carbon is fast because microorganisms prefer easily decomposable, simple organic compounds (soluble sugars, organic acids, starch, and etc.). In the mature period of compost, however, only hardly decomposable organic matter (cellulose, hemicelluloses, lignin, and etc.) are left as carbon source, slowing down the decomposition rate.

## (2) Decomposable organic matter (DOM)

In the humification process, decomposable organic matter experiences down—up—down fluctuations, and ends up with a sharp decline when the compost tends to be stable. In the heating phase, the easily decomposable organic matter reduces quickly, given the favorable high oxygen content. In the thermophilic phase, exogenous microbial activities are very active, and with organic matter decomposition, a lot of easily decomposable organic matter is produced, resulting in a rise of net organic matter. To the cooling phase, the microbial decomposition of organic matter weakens and mainly serves the needs of microorganisms themselves, so the content of organic matter tends to decrease. In the mature period, the content of decomposable organic matter stabilizes at a relatively low level.

## (3) Dissolved organic carbon (DOC) content

Generally, the DOC content shows a downward trend in the humification process. In the early phase, the DOC concentration is relatively stable because the rapid decomposition of fat and carbohydrate replenishes DOC necessary to microbial activities. As microorganisms multiply rapidly in the composting, entailing large DOC consumption, the DOC concentration is significantly reduced.

## (4) DOC composition

The DOC structure in different phase is as shown in Fig. 2.1. In the initial phase of humification, DOC is mainly comprised of simple structural protein, but with the process of decomposition, humic substances increase, making the DOC composition complex (He et al. 2014).

### 2.2.1.3 Change in Small Molecular Organic Acids (He et al. 2011a)

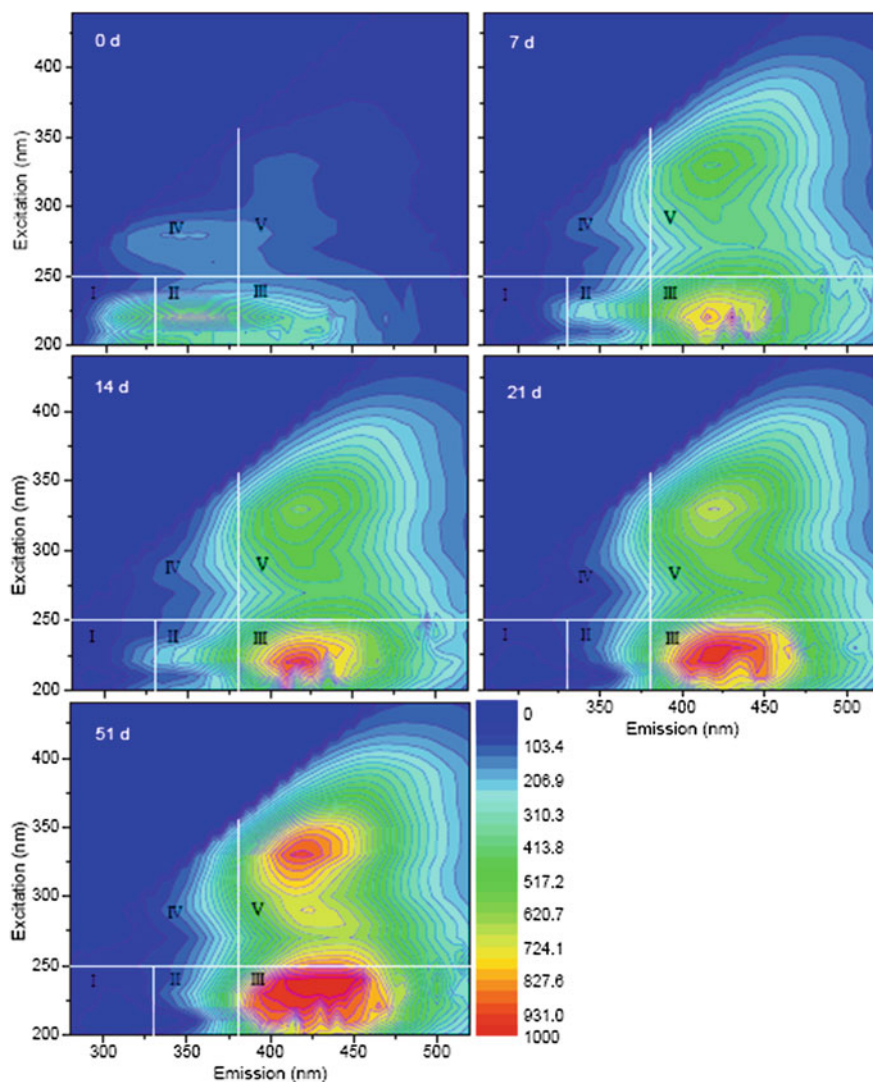
Organic acids are an important intermediate product in the humification process. A part of them are mineralized in the tricarboxylic acid cycle, providing nutrients for microbial growth, and the other part, retained as humus. It should be noted that volatile fatty acid (VFA) is the main component of malodorous gases. Small molecular organic acids affect pH in the humification process and the accumulation will acidify compost and hamper microbial growth.

#### (1) Volatile organic acids

Volatile organic acids increase considerably in the initial humification of organic waste, followed by a drastic decline afterwards. The whole humification process sees two peaks of volatile organic acids.

#### (2) Nonvolatile organic acids

Similar to volatile organic acids, nonvolatile organic acids also peak twice in the composting, though at different times.



**Fig. 2.1** Three-dimensional (3-D) fluorescence spectrograms of the DOC composition “Reprinted from He et al. (2011a, b), with permission from Elsevier”

### (3) Total organic acids

In the humification process, bioaugmentation changes greatly the total organic acids. The total organic acids produced in inoculated microbial treatment are much higher than those of exogenous microbial treatment. In late composting, the total amount of organic acids decreases drastically until the mature period, while

non-inoculated exogenous microbial treatment maintains a downward trend. Therefore, judging from organic acids, bioaugmentation can facilitate humification.

### 2.2.1.4 Change in Humus Composition and Characteristics

#### (1) Humus content

Total humus shows a positive correlation with organic carbon in the humification of organic waste process. In the early and middle phases, the humus content drops fast and exogenous microbial treatment weakens notably more than inoculated microbial treatment. Humic and fulvic acids are important components of humus that play a decisive role in the quality of humus. In the humification process, humic acids first decrease and then increase, while fulvic acids tend to decline. Fulvic acids have relatively low molecular weight and simple molecular structure. In the composting process, partly they are decomposed by microorganisms and partly converted to humic acids of large molecular weight and complex molecular structure.

#### (2) Degree of humification

Under normal circumstances, the degree of humification of the garbage compost can be represented by three parameters: humification ratio [ $HR = (HA + FA) \times 100/TC$ , where TC stands for total organic carbon], humification index ( $HI = HA/FA$ ), and percentage of humic acid ( $HP = HA \times 100/HS$ ). The HR value presents two valleys in the humification process, with an apparent increase in the mature period. Inoculating microbial agents is conducive to the formation of humus and humic acids and further humification, and makes the quality of humic acid superior.

#### (3) Humic acid spectroscopy

Aromatized humic acids are significantly enhanced with humification. In comparison, exogenous microbial treatment considerably strengthens the condensation of humic acids. As humification stabilizes, humic acids of different sources and treatments have substantially similar infrared spectral shape, but sharply differ in the intensity of absorption in characteristic peaks. This implies a massive impact of different exogenous microbial treatments on structural units and functional group content of humic acids.

### 2.2.1.5 Dynamic Changes of Organic Nitrogen

The conversion of nitrogen is subject to microbial activities and decides the final maturity. In the humification process, nitrogen is either fixed or released, depending on raw materials (Yang et al. 2006). Nitrogen is one of the main elements of organic waste. Under aerobic humification circumstances, nitrogen exists in the forms of ammonia, nitrate and organic nitrogen, and suffers large losses when the C/N ratio is low. An analysis of different nitrogen-contained matters that reveals material flow

and conversion of nitrogen will provide theoretical support for the research to optimize the nitrogen cycle and the retention of nitrogen.

#### (1) Total nitrogen

In the humification process, the total nitrogen shows a downward trend due to the loss of nitrogen in the decomposition of organic matter. Microbial fermentation involving bioaugmentation only accelerates the composting process and does not cause serious nitrogen loss.

#### (2) Dissolved organic nitrogen (DON) and insoluble nitrogen

DON accounts for about 75–95 % of and closely correlates with the total nitrogen (He et al. 2015). In the early phase, DON exhibits a downward trend and the treatment of DON with exogenous microorganisms is low, suggesting that exogenous microbes accelerate organic nitrogen mineralization in the humification process.

#### (3) Amino nitrogen

Amino is a major form of DON. Studies show that amino nitrogen accounts on average for about 33.04 % of and closely correlates with DON. Microbes are conducive to the accumulation of amino nitrogen in the late humification process.

#### (4) Amide nitrogen

Amide accounts on average for about 18.16 % of DON. In the heating and thermophilic phases, amide nitrogen is increasing, but in the cooling phase, declines significantly until enters a stable state. The entire process sees a notable decrease of amide treatment with exogenous microorganisms, indicating that exogenous microorganisms can reduce the generation of amide nitrogen.

#### (5) Amino sugar nitrogen

Amino sugar nitrogen, an important component of microbial life, is closely related with microbial biomass. It increases gradually with microbial biomass in the humification process, and drops markedly with the death and decomposition of microorganisms. The content of amino sugar nitrogen tends to stabilize when the compost matures.

#### (6) Nitrogen in unknown forms

Nitrogen also exists in nucleic acids and their derivatives, phospholipids, vitamins and other derivatives. As composting proceeds, nitrogen in unknown forms decreases, notably in the heating phase. Within 7–63 days, there are complex changes of microbial treatments, but comparatively speaking, exogenous microbial treatment does not cause excessive loss of nitrogen. Exogenous microbial treatment only accelerates the decomposition of organic matter and in a sense, shortens the humification period. Regardless of phase, exogenous microbial treatment of amide nitrogen is always less than non-vaccinated, while amino sugar nitrogen exhibits

the opposite trend with amide nitrogen, with no significant differences between the various exogenous microbes.

#### **2.2.1.6 Phosphorus Conversion**

##### **(1) Organic phosphorus**

Humification is accompanied by organic phosphorus mineralization, but the total amount of organic phosphorus still increases gradually in the humification process. It can be attributed to two reasons: (a) decomposition at a greater rate than mineralization maintains the relative content of organic phosphorus and (b) dissolved phosphorus released in the mineralization has been reused as a component of microbial life in the compost.

##### **(2) Dissolved phosphorus**

Dissolved phosphorus first decreases and then increases in the humification process. The content is reduced in the heating phase due to the use of phosphorus for microbial reproduction and metabolism. In the cooling phase, the demand for phosphorus decreases with the end of metabolic process and dead microbes are mineralized, pushing up dissolved phosphorus content in the compost.

##### **(3) Rapidly available phosphorus**

Rapidly available phosphorus content shows an upward trend in the humification process. The introduction of insoluble ground rock phosphate to the humification of organic waste will significantly increase the content of rapidly available phosphorus, while low molecular weight organic acids and microbes will accelerate the conversion of ground rock phosphate.

#### **2.2.1.7 Microbial Communities**

In the aerobic humification process, cultivable bacteria increase followed by a decrease. In the heating phase when the temperature is relatively low, mesophilic microorganisms, including bacteria and fungi, mainly live in the compost and degrade organic matter. Due to slow propagation velocity, the fungi population is much smaller than the bacteria population. Generally, microbial communities are related with the organic waste composition and microbial species are very rich. After entering the thermophilic phase when the temperature is not less than 50 °C, a large number of mesophilic microorganisms die and most fungi turn to spores or die at a temperature greater than 60 °C. Thermophilic bacteria take a dominant position, and thermophilic *Bacillus* or heat-resistant microorganisms become the primary bacterial population of the compost. In the thermophilic phase, organic matter decomposition speeds up with fast growth, reproduction, and metabolism of bacteria and organic matter soluble in water. In the cooling phase, thermophilic

microorganisms gradually lose dominance because of the lack of organic matter. When the compost temperature continues to fall below 50 °C, mesophilic microorganisms become alive again and mesophilic fungi and actinomycetes that degrade macromolecule organic matter become dominant populations (Li et al. 2012).

### ***2.2.2 Anaerobic Digestion of Organic Waste***

Anaerobic digestion of solid waste is also known as anaerobic fermentation, a process of organic matter decomposition with CO<sub>2</sub> and CH<sub>4</sub> generation under anaerobic conditions by a variety of (anaerobic or facultative anaerobic) microbes (Jia et al. 2014). By means of anaerobic digestion, solid waste can be made harmless, reduced, stabilized and used. Anaerobic digestion is considered a sustainable treatment technology, owing to such advantages as low cost, high efficiency, small footprint, and low energy consumption.

#### **2.2.2.1 Theory**

Anaerobic fermentation is generally considered to involve three stages, namely hydrolysis, acidogenesis and methanogenesis (Li et al. 2014). Throughout the whole process, the three bacteria communities (fermentation bacteria, acidogenic and acetogenic bacteria, methanogens) interact with each other, eventually degrading complex organic compounds into CH<sub>4</sub> and H<sub>2</sub>.

##### **(1) Hydrolysis**

Hydrolysis is the first important process of anaerobic fermentation, in which insoluble complex polymers are broken down to soluble monomers or dimers. Organic polymers with large molecular weight cannot pass through the cell membrane and can be directly used by bacteria only when hydrolyzed by extracellular enzymes into small molecules. The rate and extent of hydrolysis is affected by many factors, including temperature, pH, organic matter components (such as lignin, protein and fat content, and carbohydrates), particle size of organic matter, content of ammonia, and hydraulic retention time. A key pre-condition for hydrolysis is the direct contact between extracellular enzymes and the substrate. Where plant residues serve as the substrate, the extent of cellulose and hemicelluloses wrapped by lignin determines biodegradability.

As far as kitchen waste is concerned, hydrolysis generally performs fast due to high water content, rich organic matter, large proportion of carbohydrates, and low lignin content. Under anaerobic conditions, the protein, which accounts for about 20 % of kitchen waste, is hydrolyzed into polypeptide and amino acid and further acidified to VFA and H<sub>2</sub>. Under normal circumstances, the proteolysis rate is very slow because the original protein folder (such as hydrogen bonding) is not sensitive



to degradation. In this sense, proteolysis is a rate-limiting step for the hydrolysis of kitchen waste with high protein content.

## (2) Acidogenesis and acetogenesis

Fermentation refers to the biodegradation process following hydrolysis in which organic molecules can be used as an electron acceptor and at the same time, an electron donor. Acidification is a process that dissolved organic matter (DOM) is converted into VFA-dominated end products.

Acidification end products are determined by anaerobic fermentation conditions, substrate, and microbial populations involved in acidification. They are different, depending on the structure and nature of substrate. The acidification process sees the generation of acetic acid, accompanied by such VFAs as butyric acid and lactic acid which are further metabolized by acetic acid bacteria to acetic acid,  $H_2$  and  $CO_2$ . According to end products, fermentation can be divided into three categories: butyric acid fermentation, propionic acid fermentation and ethanol fermentation. The end products of butyric acid fermentation mainly include butyric acid, acetic acid,  $H_2$ ,  $CO_2$  and a small amount of propionic acid. Propionic acid fermentation ends up with propionic acid and acetic acid, while ethanol fermentation ends up with ethanol, acetic acid,  $CO_2$  and  $H_2$ .

## (3) Methanogenesis

In the anaerobic digestion, the carboxyl of acetic acid is separated from molecule and converted to  $CO_2$ , while methyl is converted to  $CH_4$ . The matrix used by methanogens is largely simple carbon compounds containing one or two bonded carbon atoms. In an anaerobic reactor, methanogenic bacteria and methanogenic coccus are dominant species, such as *methanosarcina barkeri* and *methanobacterium sohngei*. When the acetic acid concentration is low, *methanobacterium sohngei* grows faster, but given high  $CH_4$  concentration, the bacteria growth increases with the acetic acid concentration. *Methanosarcina barkeri* is likely to take a dominant position when acetic acid accumulates. Given  $CO_2$  and  $H_2$ ,  $CH_4$  can also be synthesized by hydrogen-oxidizing methanogens, and when the reactor runs stably,  $CH_4$  generated this way can account for 30 % of the total.

### 2.2.2.2 Hydrothermal Hydrolysis

#### (1) Crude protein

Crude protein is one of the target products of biomass value maximization using hydrothermal hydrolysis. LamoolPhak held that in the hydrothermal system, raised processing temperature and shortened processing time is an important condition for obtaining high yields of protein. Watchararui found that protein solubility in water enhances with ionization of water, while the degree of ionization increases with temperature. Compared with the control group, the crude protein content increases at 80 and 120 °C, but decreases at 150 and 200 °C. It means that such a temperature

as 80 and 120 °C makes crude protein colloids hydrolyzed, but does not affect the high-level structure of protein, resulting in a lower degree of hydrolysis. Under the above described conditions, such macromolecules as carbohydrates and lipids are liquefied or leached more than crude protein, pushing up the crude protein content. As the temperature continues to rise, changing the internal structure and affecting the peptide bond, the protein solubility is significantly enhanced, so the crude protein content is relatively reduced at 150 and 200 °C.

## (2) VFAs

The total amount of liquid VFA increases markedly after hydrothermal hydrolysis. It indicates that with the enhancement of water ionization, the degree of hydrolysis of macromolecular protein substances increases, lowering down the content of small molecular organic acids in the degradation products. Studies found that small molecules formed in a hydrothermal system have a certain catalytic effect on degradation of macromolecules. The VFA content is more impacted by temperature than time and water. In terms of the VFA composition, hydrothermal hydrolysis greatly affects acetic acid, butyric acid and ethanol. Compared with the control group, acetic acid and butyric acid are noticeably higher, while the ethanol content decline substantially. It implies that hydrothermal hydrolysis tends to convert organic matter to acetic acid.

## (3) Crude fat and oil slick

Oil slick is an important parameter affecting garbage biochemical pathways. It contains a large amount of long-chain fatty acids (LCFAs) which are adsorbed on the cell surface to limit the transport of nutrients to cells, thus inhibiting microbial growth and impairing the subsequent biochemical treatment efficiency. As far as kitchen waste is concerned, oil slick is closely related to the crude fat content and can be dramatically increased after hydrothermal hydrolysis. Crude fat can be hydrolyzed to glycerin and fatty acids which further facilitate hydrolysis by esterification with sugar. Meanwhile, hydrothermal hydrolysis enhances the diffusion of solid fat of kitchen waste in water and accelerates the formation of oil slick, lowering down the solid fat content.

## (4) Sugar

Sugar is an important carbon source for microbial growth. It can also be directly used or converted into other materials or energy. It is mainly derived from carbohydrate hydrolysis, in which carbohydrate collides with hydronium ions ( $\text{H}_3\text{O}^+$ ) or hydroxide ( $\text{OH}^-$ ) and breaks down into monomers, i.e. reducing sugar, when the glycosidic bond is broken. In a hydrothermal system, the average kinetic energy of motion of molecule increases with temperature, and intensifies the ionization of water, exerting a larger effect on the glycosidic bond. When the temperature reaches 150 and 200 °C, carbohydrates are highly liquefied, increasing the content of reducing sugar. The total sugar content has the consistent trend with that of reducing sugar.

### 2.2.2.3 Intermediates (VFAs and Ethanol)

The different processes in anaerobic digestion exert a significant impact on the composition and conversion of VFAs in fermentation.

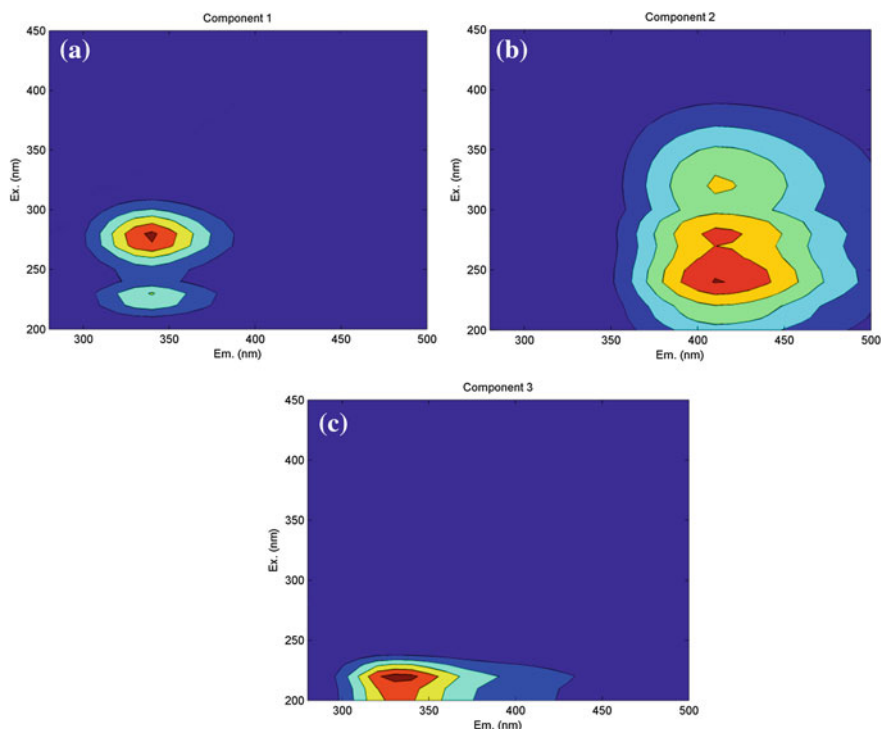
VFAs are an important intermediate product in the anaerobic metabolic process. Studies found that, the concentration of acetic acid first increases and then decreases, and peaks in the second day in the groups with heat-moisture treatment, while in the control group, the peak of acetic acid concentration arrives in the third day. Under the conditions of 150 °C, 60 min, and 40 % water, the cumulative amount of acetic acid registers the highest of 11,243.66 mg/L and the cumulative H<sub>2</sub> amount also reaches the peak. This further proves that heat-moisture treatment accelerates the rate of hydrolysis and acidification and improves the efficiency of H<sub>2</sub> production. In addition, under these conditions, the propionic acid level is higher than that of other experimental groups. Among VFAs, propionic acid, with the slowest conversion to acetic acid and supreme toxicity, seriously restrains the activity of methanogenes and represses the conversion of organic matter to small molecule acids, thus hindering the CH<sub>4</sub> generation. Butyric acid exhibits similar changes with acetic acid. The maximum content, recording 6268.87 mg/L, is also seen under the conditions of 150 °C, 60 min, and 40 % water. Butyric acid fermentation is common in anaerobic fermentation, and it is butyric and acetic acid fermentation that generate H<sub>2</sub>. This is positively correlated with the change in H<sub>2</sub> production. In the control group, liquid propionic and butyric acids are least and cumulative acetic acid relatively low, which coupled with highly active methanogenes, gives rise to the highest cumulative CH<sub>4</sub> production.

### 2.2.2.4 Reducing Sugar

Reducing sugar is sugar that can form aldehyde and ketone groups in an alkaline solution and be oxidized by appropriate agents to aldonic acid, saccharic acid, monosaccharides including glucose, fructose and glyceraldehyde, disaccharides including lactose and maltose, as well as oligosaccharides. Reducing sugar can be directly used by microorganisms and the measurement can facilitate the observation of microbial growth. Hence, the routine measurement of reducing sugar is commonly applied to monitor the microbial growth on large-scale industrial production. In the anaerobic digestion of food waste, the concentration of reducing sugar decreases after the initial increase and reaches the highest in about 150–250 h.

### 2.2.2.5 Fluorescent Substances

A parallel factor analysis of the 3-D fluorescence spectra of effluent from the anaerobic digestion reactor of food waste is conducted, the results are as shown in Fig. 2.2. For Component 1, excitation occurs at a wavelength of 225 and 280 nm and emission 340 nm, respectively corresponding to tryptophan substances and



**Fig. 2.2** Three-dimensional fluorescence spectrograms by anaerobic fermentation processes

soluble microbial metabolites. For Component 2, excitation occurs at a wavelength of 250 and 330 nm emission 420 nm, which corresponds to the fluorescence contribution of coenzyme NADH and fulvic acids. For Component 3, excitation is positioned at 220 nm and emission 330 nm, corresponding to the fluorescence contribution of protein components.

Judging from the score by fluorescence intensity, Component 2 shows basically the same trend of increase with the duration of anaerobic fermentation in different processes. In anaerobic fermentation process, NADH accumulates in the absence of electron transport chain. Coenzyme NADH has 460 nm UV light fluorescence emission at 340 nm, while the fluorescence for the oxidation state  $\text{NAD}^+$  is not observed. In the process of oxidative phosphorylation, NADH transfers electrons to oxygen and is oxidized to  $\text{NAD}^+$ . The process is inhibited by limited oxygen, leading to NADH accumulation, as fluorescence shown in parallel factor analysis. Accordingly, such characteristics can be applied and monitored. When the reactor is not confined strictly and the anaerobic environment is destroyed, the NADH fluorescence will suddenly reduce.

### 2.2.3 Solid Waste Landfill

Landfill is a major way to dispose solid waste, in which the organic components are stabilized under the action of microorganisms. It is very important to study the generation and conversion of landfill gas and leachate which is the core of landfill operation and secondary pollution control (Cai 2003).

#### 2.2.3.1 Landfill Gas Generation, Migration and Transformation

Landfill gas generation is a very complex process. The key lies in the biochemical reaction of anaerobic fermentation and decomposition of organic matter in the waste that produces  $\text{CH}_4$  and  $\text{CO}_2$ . According to the type of reaction, the process of organic matter decomposition can be divided into four stages: aerobic decomposition, anaerobic hydrolysis and acidification, anaerobic aerogenesis, and oxidation.

Landfill gas generation rate is described by the following formula:

$$\alpha_k(t) = \sum_{i=1}^3 C_{Ti} A_i \lambda_i e^{-\lambda_i t} \quad (2.2.1)$$

where in  $i$  represents the three components of waste (easily, moderately, and hardly decomposable substances);  $\alpha_k$  indicates the annual gas generation rate for gas  $k$  ( $\text{kg}/\text{m}^3$ );  $C_{Ti}$  indicates the potential total gas generation rate for gas  $k$  in component  $i$  ( $\text{kg}/\text{m}^3$ );  $A_i$  means the content of component  $i$  and  $\lambda_i$  the corresponding gas generation constant ( $\text{yr}^{-1}$ );  $t$  stands for time ( $\text{yr}$ ).

In case of ignoring the diffusion change over time, landfill gas changes can be calculated, using the following formula:

$$\begin{aligned} & \frac{\partial}{\partial X} (D_{ekm} \frac{\partial \rho_k}{\partial X}) + \frac{\partial}{\partial Y} (D_{ekm} \frac{\partial \rho_k}{\partial Y}) + \frac{\partial}{\partial Z} (D_{ekm} \frac{\partial \rho_k}{\partial Z}) + \alpha_k(Z) \\ &= \frac{\partial (V_X \rho_k)}{\partial X} + \frac{\partial (V_Y \rho_k)}{\partial Y} + \frac{\partial (V_Z \rho_k)}{\partial Z} \end{aligned} \quad (2.2.2)$$

where in:  $V_{x,y,z}$  represents the velocity in direction  $x$ ,  $y$ , and  $z$  respectively;  $\rho_k$  stands for the mass concentration of gas  $k$  in the gas mixture ( $\text{kg}/\text{m}^3$ ).

Based on the basic fluid dynamics in porous media theory, a three-dimensional mathematical model is constructed for landfill gas migration and transformation and the finite element and iterative methods introduced to facilitate calculation. Further, the MATLAB visual simulation is carried out, providing a theoretical basis the utilization of landfill gas and control of secondary pollution. In the simulation of landfill gas generation, migration and transformation in an 8 year old landfill, the total pressure reaches the maximum of 23 Kpa in the middle of the landfill, and decreases gradually from the middle to the edges, indicating that the dominant direction of gas transport is from the boundary toward the center in the case of

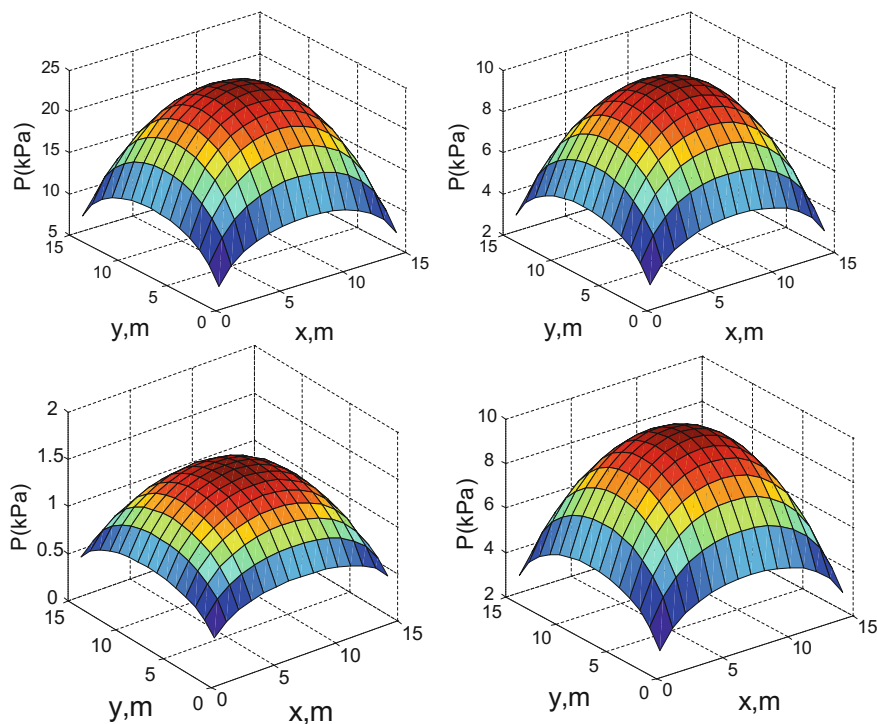
impermeable boundaries. The distribution of pressure may be due to high gas generation rate with fast microbial degradation of organic waste at high temperature in the middle and low gas production rate at a low ambient temperature.

Landfill gas is composed of  $\text{CH}_4$  and  $\text{CO}_2$  and a small amount of  $\text{O}_2$  and  $\text{N}_2$ .  $\text{CH}_4$  and  $\text{CO}_2$  are produced from strong sources, i.e. microbial degradation of waste, and take a large proportion in the total pressure (Fig. 2.3), and  $\text{N}_2$  is generated only from a small source and gradually diffused beyond the landfill system. As landfill turns old, gas production first increases and then decreases.

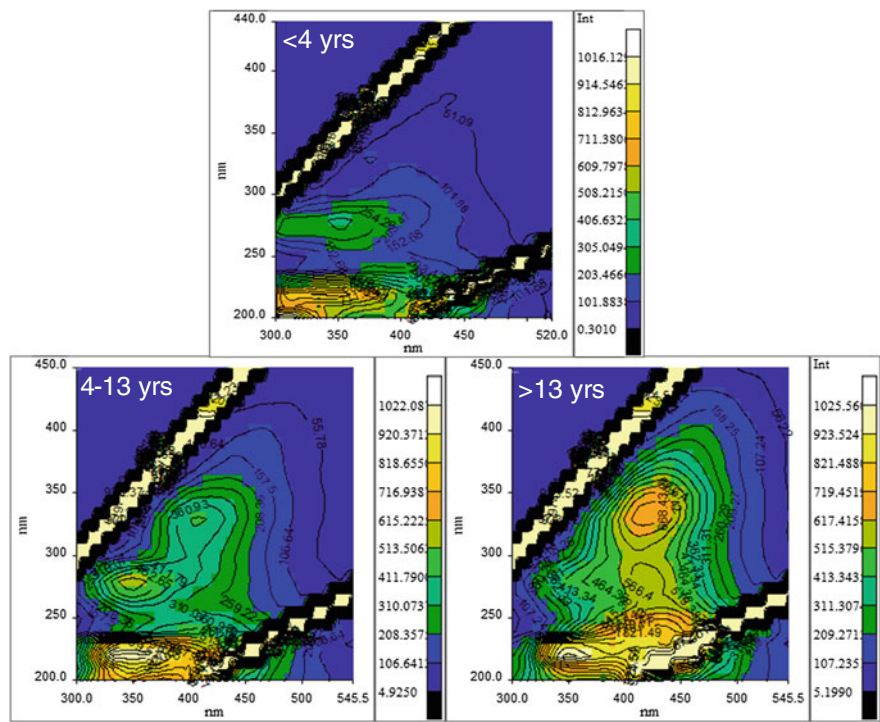
### 2.2.3.2 Leachate Generation, Migration and Transformation

Landfill leachate is organic wastewater with high organic content, and leachate characteristics vary, depending on the landfill age and leachate treatment stages (Cao et al. 2004; Li et al. 2008). A clear understanding of the characteristics of organic pollutants is important for preventing and controlling the spread of contamination and but also lays the basis for the actual leachate treatment and operating parameters (Chen et al. 2005).

In this study, three-dimensional fluorescence spectroscopy, infrared spectroscopy and elemental analysis are combined to follow up organic matter changes at landfills of different ages and in leachate treatment stages (Fig. 2.4).



**Fig. 2.3** Total pressure changes with depth



**Fig. 2.4** Fluorescence spectrograms for DOM in leachate at landfills of different ages

DOM fluorescence spectra show four kinds of fluorescent peaks including protein-like fluorescence and humic-like fluorescence. At young landfills, the peak occurs in protein-like fluorescence, and DOM mainly consists of simple-structured protein-like substances. At middle-aged and old-age landfills, leachate mainly contains fulvic-like substances and humic-like substances, largely hardly decomposable organic matter. In the landfill reactor simulation, the 3-D fluorescence peak of leachate gradually shifts from protein-like fluorescence to humic-like fluorescence, indicating an increased degree of decomposition.

Protein-like substances can be easily removed through biological processes and humic-like substances through reverse osmosis process. The analysis of fluorescence properties can facilitate the rapid determination of characteristics of organic matter dissolved the leachate sample. Infrared spectroscopy quantifies the changes in properties of organic matter by analyzing chemical groups and bands of substances in the sample and DOM structural changes. The results show that with the humification degree and aromatic series of leachate increase with the age of landfill.

DOM is the most important contaminant of leachate. It can interact with other toxic substances in environmental media, producing composite pollution and impacting migration and transformation of the latter and bioavailability.

- (1) DOM in initial landfill leachate mainly contains protein-like substances, but with the extension of landfill life, humic-like substances appear and take an increasing percentage in DOM, and the condensation of molecules increases, strengthening humification. Studies revealed that the specific way of landfill has a notable impact on the DOM composition. In the case of layered landfill, fresh leachate migrates downward along the section, resulting in increased protein-like substances in DOM of underlying aged leachate. This will impact the migration and transformation of pollutants in the media.

In the four DOM groups of different polarities and charges, the hydrophobic acid (HOA) in leachate initially includes tyrosine-like substances, and late, fulvic-like and humic-like substances. Hydrophilic matter (HIM) is embodied in tryptophan-like substances, tyrosine-like substances, fulvic-like and humic-like substances in the early, middle and late stages of landfills respectively, indicating complex structure of organic matter over time. Hydrophobic bases (HOB) and hydrophobic neutrals (HON) remain protein-like substances all the time, but there are fulvic-like and humic-like substances in aged leachate (Fig. 2.5).

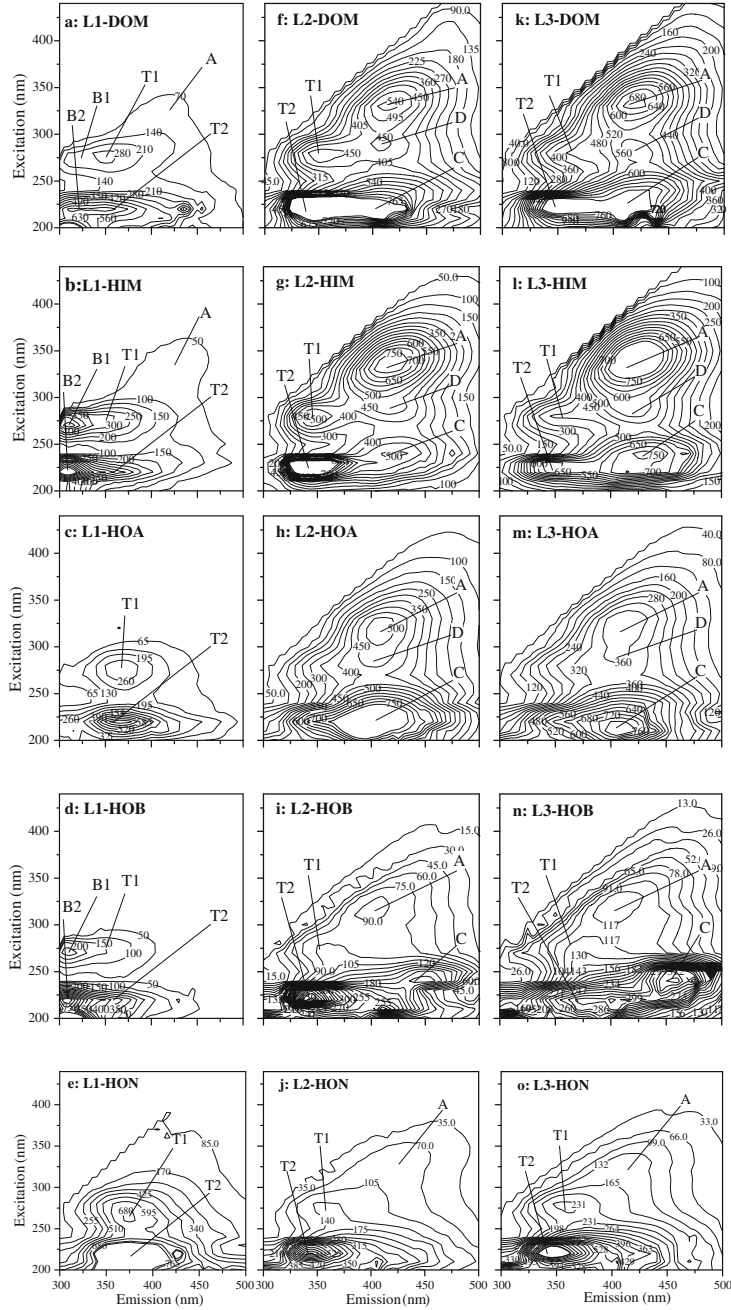
Biological treatment is suitable for young landfill leachate, while physico-chemical methods, such as reverse osmosis process, are applicable to aged leachate. The volume ratio of characteristic fluorescences between humic-like substances (Region V + VI) and protein-like substances (Region I + II + III + IV) is used to evaluate the stability of organic matter, and further forecast and optimize leachate treatment techniques (Fig. 2.6).

- (2) HOA is the major component of DOM in the leachate, and increases with the age of landfill. Humic-like substances show increased formation capability and weaken the mobility and bioavailability of such environmental pollutants as mercury. HIM decreases over time, of which humic-like substances become less able in the complexation of mercury and reduce the mobility and bioavailability of other toxic substances (Table 2.1). Hence, with the extension of landfill life, the secondary environmental effect of DOM in the leachate abates. HON and HOB of low content have limited impact on DOM's environmental effects.

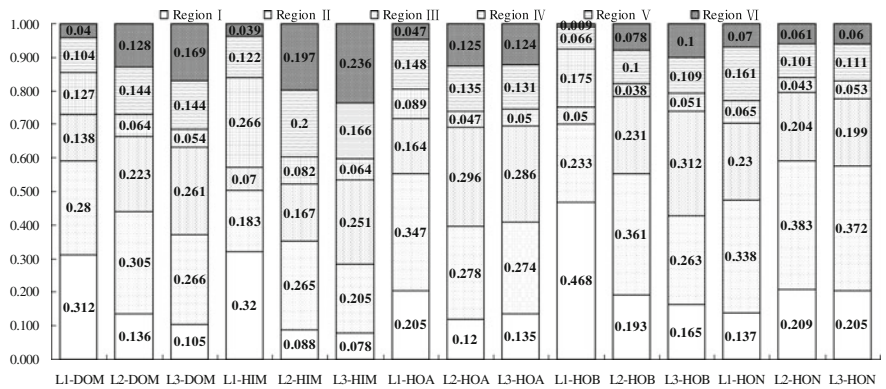
DOM consists of two typical components: protein-like substances and humic-like substances. Protein-like substances significantly improve the bioavailability of heavy metals and the secondary environmental effects because they are more able in the complexation of heavy metals (mercury) and easy to use and degrade.

- (3) The process of bonding DOM and heavy metals in leachate is subject to the pH of media, notably in the acidic and basic solutions. When the pH is lower than 5, the carboxyl group has the dominant role, and when the pH is high ( $\text{pH} > 9$ ), the phenolic hydroxyl group plays an important role. When the pH ranges from 6 to 9,  $\beta$ -dicarboxy compounds, alcohols, and inorganic substrate on the surface undergo weak dissociation, so there will be little change in the organic matter's ability to bond heavy metals.





**Fig. 2.5** Three-dimensional fluorescence spectrograms of DOM and its components in leachate by landfill ages “Reprinted from He et al. (2011a), with permission from Elsevier”



**Fig. 2.6** Change in the DOM composition over time “Reprinted from He et al. (2011b), with permission from Elsevier.”

**Table 2.1** Content of different components and formation constants for characteristic peaks and characteristic fluorescence

	Component	Content ratio (%)	Formation constant			
			Peak T1	Peak T2	Peak C	Peak A
<3 years	HOA	52.25	5.27	5.20	4.20	4.31
	HON	6.96	5.60	5.38	5.48	5.20
	HIM	39.12	5.63	5.46	4.82	5.40
3–10 years	HOA	55.86	4.66	4.59	4.22	4.35
	HON	5.86	5.29	4.93	5.08	5.42
	HIM	37.39	5.24	4.95	4.79	4.99
>10 years	HOA	61.59	5.27	5.13	4.65	4.56
	HON	5.80	5.38	4.71	5.48	4.90
	HIM	31.16	5.76	5.50	4.13	3.88
	Average		5.34	5.09	4.76	4.78

### 2.3 Technical Methods for Dynamic Multi-objective Optimization of Solid Waste Management

The complex components and large uncertainty of solid waste makes is difficult to weigh the system costs and environmental benefits, posing a severe challenge to the stability and socioeconomic benefits of disposal techniques. This section constructs a model for dynamic multi-objective optimization of solid waste management in uncertain environments based on the considerations of pollution loss, interval uncertainty, infinite programming, and chance-constrained two-stage (CCTS) programming. An optimization system for multi-attribute decision making is built, mitigating the effect of subjectivity and asymmetric information on

decisions. On the basis, an optimization-validation-feedback management mechanism that cuts the system costs by 20 % is set forth, conducive to an effective balance of environmental and economic benefits.

### 2.3.1 Construction of the Model for Dynamic Multi-objective Optimization Under Uncertainty

In the context of China's municipal solid waste (MSW) management, considering multiple objectives, uncertainty and constraints, a model for dynamic multi-objective optimization is proposed on the basis of multi-objective planning, pollution loss theory, and uncertainty analysis. The model well integrates economic and environmental aspects and facilitates an objective solution to optimal management of municipal solid waste (Su et al. 2007).

#### 2.3.1.1 General Form of Formula and Solution

The formula of uncertain linear programming can be expressed as follows:

$$\text{Min } f^{\pm} = C^{\pm}X^{\pm} \quad (2.3.1a)$$

$$\text{s.t. } A^{\pm}X^{\pm} \leq B^{\pm} \quad (2.3.1b)$$

$$X^{\pm} \geq 0 \quad (2.3.1c)$$

where,  $X^{\pm} \in \{\Re^{\pm}\}^{n \times 1}$ ,  $C^{\pm} \in \{\Re^{\pm}\}^{1 \times n}$ ,  $A^{\pm} \in \{\Re^{\pm}\}^{m \times n}$ ,  $B^{\pm} \in \{\Re^{\pm}\}^{m \times 1}$ ;  $\Re^{\pm}$  represents a collection of uncertain numbers.

#### 2.3.1.2 Solution of Formula

In the above-mentioned uncertain linear programming formula, the solution necessitates a thorough analysis of the relationship between parameters and variables and between the objective function and constraints. According to Huang et al., an interactive two-step approach can be used: (a) construct and solve the sub-formula for the lower objective function limit  $f^{-}$  (for MIN) and (b) construct and solve the sub-formula for the upper objective function limit  $f^{+}$ , obtaining the uncertain solution of formula. Here is the specific solving process:

In  $n$  uncertainty factors of objective function,  $c_j \pm$  ( $j = 1, 2, \dots, N$ ), it is assumed that there are  $k_1$  positive numbers and  $k_2$  negative numbers. In other words, the first  $k_1$  factors are positive, i.e.  $c_j \pm \geq 0$  ( $j = 1, 2, \dots, k_1$ ), and the late  $k_2$  are negative, i.e.  $c_j \pm < 0$  ( $j = k_1 + 1, k_1 + 2, \dots, n$ ) and  $k_1 + k_2 = n$  (the case of different symbols for

lower and upper limits is not included). The algorithm for solving uncertain linear programming problems is as follows:

In the framework of formulas 2.3.1a, b, c the sub-formula for the lower objective function limit  $f^-$  can be constructed as follows, (assuming  $b_i \pm > 0$ ):

$$Min f^- = \sum_{j=1}^{k_1} c_j^- x_j^- + \sum_{j=k_1+1}^n c_j^- x_j^+ \quad (2.3.2a)$$

$$s.t. \sum_{j=1}^{k_1} |a_{ij}|^+ Sign(a_{ij}^+) x_j^- / b_i^- + \sum_{j=k_1+1}^n |a_{ij}|^- Sign(a_{ij}^-) x_j^+ / b_i^+ \leq 1, \forall i \quad (2.3.2b)$$

$$x_j^\pm \geq 0, j = 1, 2, \dots, n \quad (2.3.2c)$$

The sub-formula for the upper objective function limit  $f^+$  is built on solution of formulas 2.3.2a, b, c,  $x_{j_{opt}}^-$  ( $j = 1, 2, \dots, K_1$ ) and  $x_{j_{opt}}^+$  ( $j = k_1 + 1, k_2 + 2, \dots, n$ ), (assuming  $b_i \pm > 0$ ):

$$Min f^+ = \sum_{j=1}^{k_1} c_j^+ x_j^+ + \sum_{j=k_1+1}^n c_j^+ x_j^- \quad (2.3.3a)$$

$$s.t. \sum_{j=1}^{k_1} |a_{ij}|^- Sign(a_{ij}^-) x_j^+ / b_i^+ + \sum_{j=k_1+1}^n |a_{ij}|^+ Sign(a_{ij}^+) x_j^- / b_i^- \leq 1, \forall i \quad (2.3.3b)$$

$$x_j^\pm \geq 0, j = 1, 2, \dots, n \quad (2.3.3c)$$

$$x_j^+ \geq x_{j_{opt}}^-, j = 1, 2, \dots, k_1 \quad (2.3.3d)$$

$$x_j^- \leq x_{j_{opt}}^+, j = k_1 + 1, k_1 + 2, \dots, n \quad (2.3.3e)$$

If the objective function is MAX (which requires maximization), the constructing and solving process is contrary to the above. Formulas (2.3.2a, b, c) and (2.3.3a, b, c, d, e) can be adapted to common single-objective linear programming problems. The optimal solution of the formulas (2.3.2a, b, c)  $f_{opt1}^-$  can be obtained, i.e.  $x_{j_{opt}}^-(j = 1, 2, \dots, K_1)$  and  $x_{j_{opt}}^+(j = k_1 + 1, k_2 + 2, \dots, n)$ , and the optimal solution of the formulas (2.3.3a, b, c, d, e)  $f_{opt1}^+$ , i.e.  $x_{j_{opt}}^+(j = 1, 2, \dots, K_1)$  and  $x_{j_{opt}}^-(j = k_1 + 1, k_2 + 2, \dots, n)$ . Based on this, the final solution is concluded as  $f_{opt1}^\pm = [f_{opt1}^-, f_{opt1}^+]$  and  $x_{j_{opt}}^\pm = [x_{j_{opt}}^-, x_{j_{opt}}^+]$ .

### **2.3.2 *Model for Dynamic Multi-objective Optimization Under Uncertainty***

#### **2.3.2.1 Principles of Optimization**

##### **(1) Reasonable layout and operability**

The model is suitable for optimizing the management of solid waste disposal in large and medium-sized cities. As the management involves a large scope and a variety of factors, consideration should be given to urban development and optimization model before ultimately determining a rational layout scheme.

Optimization results rest on implicit assumption about ideal conditions. On the one hand, the results of optimization model should be taken as the scientific basis to maximize economic and environmental benefits. On the other hand, the modeling results should be appropriately adjusted according to actual conditions and economic factors to conform to the comprehensive economic and environmental needs (Su et al. 2007).

##### **(2) Coordination with regional economic development and planning**

An optimization model is a phased scientific planning that forecasts the ways and means for solid waste disposal and management in case cities in the next 15–20 years. It encompasses the near-, medium- and long-term development planning and special planning for solid waste treatment and disposal. Hence, an optimization model should take full account urban planning objectives and programs to keep consistency and improve the operability.

##### **(3) Advanced and acceptable technologies**

In light of long planned period and accelerating technological progress, it is important to keep abreast of the international solid waste disposal technologies and management methods. The selection of most suitable waste disposal approaches should take into account the advancement and usefulness of technologies while drawing on the experience of the developed countries and advanced domestic practice.

Putting social and environmental benefits in the first place, a forward-looking view that considers the needs of future development is also necessary to form objectives and programs of solid waste management in different stages. The programs should ensure the optimal use of capital, technical and land resources as well as facilities, in order to achieve resourcization and sustainability of solid waste disposal.

##### **(4) Integrity and regional sharing**

The urban area is expanding with the accelerated pace of urbanization. Land, capital and technical resources should be configured at the regional level to achieve regional sharing of facilities and resources. According to the systems theory and the

synergetic theory, focus should be put on solid waste disposal planning and the effects. The application of optimization models, with a view to minimize the system cost and environmental impact, is expected to break the previous administrative boundaries of cities and facilitate the systemic planning and optimization management of MSW disposal.

### 2.3.2.2 Planning Scope and Objectives

Principles mentioned above ensure the effectiveness and operability of optimization. The geographical scope of planning should cover the municipal domain of cities and can refer to the development planning for city system, taking into account the suburbs and suburban areas.

In terms of time span, near-, medium- and long-term development planning can be formulated, according to the development plans of cities. To keep in line with the plans for national economic and social development, the short and medium term is generally considered as 5 years and the long term, 20 years (Wan et al. 2005).

The optimization model covers the whole process of waste management, including generation, collection, transportation and disposal. Generally, landfill, composting, and incineration are the major methods for waste disposal in China. Incineration and composting residues are delivered to landfills, so landfill is considered as the final disposal of waste. Economic benefits can be obtained by selling composting products. The whole process is as shown in Fig. 2.7.

According to the overall goals of regional economic and social development and the basic principles of optimal planning, the targets for MSW minimization, recycling and harmless treatment should be set out by scope and stage, including trash removal area and removal rate, separate collection rate and recycling rates, harmless treatment rate, and volume of landfills, as well as levels of mechanization, closure, and modernization.

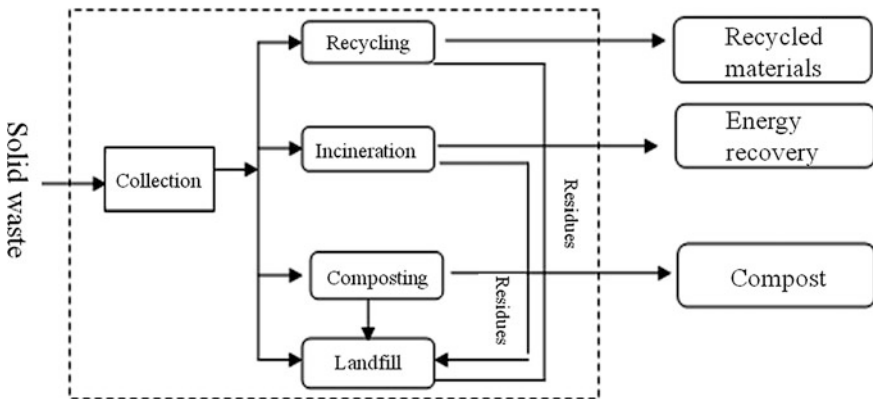
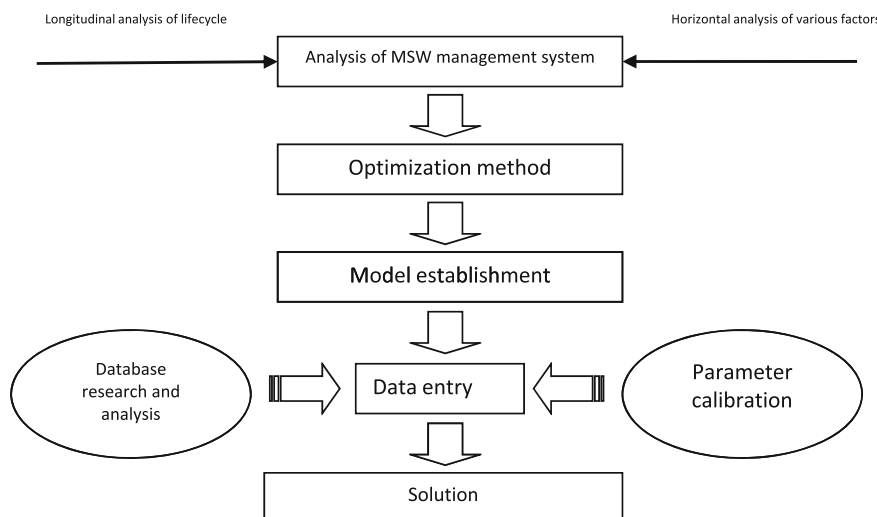


Fig. 2.7 Whole process of solid waste optimization management (Su 2007)



**Fig. 2.8** Procedure for building an optimization model for MSW management (Su 2007)

### 2.3.2.3 Procedure for Building an Optimization Model

The MSW management system is very complex, comprehensive, open, dynamic and uncertain (Zhang et al. 2014). Considering these characteristics, it is suggested to (1) construct an optimization model reflecting regional characteristics based on the scientific analysis of the management system and research of various model; (2) build a modeling framework and conduct database research and analysis and parameter calibration, to form a complete optimization model for MSW management; and (3) in accordance with the solution method, input parameters and obtain the optimal solution (Fig. 2.8).

### 2.3.2.4 Optimization Model

#### (1) Objective function

The model is designed to minimize system costs and environmental impact. The constraints include facilities capacity, waste disposal needs, mass balance, ash volume constraints, landfill capacity constraints, pollutant emissions and non-negative constraints. The system costs cover transportation costs, transit fees, processing fees, and material and energy recovery income. The environmental impact is embodied in the costs to reach the national emission standards in the control of secondary pollution from composting, incineration, and landfill (Xi et al. 2007). According to the mentioned objectives and constraints, the function for optimization model is expressed as:

$$\begin{aligned}
MinZ1^{\pm} = & \sum_o \sum_r \sum_t \frac{(DIS_{ort} \times CYF_t^{\pm} + CZF_t^{\pm} + CRF_{ort}^{\pm})X_{ort}^{\pm}}{(1+q)^t} \\
& + \sum_o \sum_l \sum_t \frac{(DIS_{olt} \times CYF_t^{\pm} + CZF_t^{\pm} + CLF_{olt}^{\pm})X_{olt}^{\pm}}{(1+q)^t} \\
& + \sum_o \sum_i \sum_t \frac{(DIS_{oit} \times CYF_t^{\pm} + CZF_t^{\pm} + CIF_{oit}^{\pm})X_{oit}^{\pm}}{(1+q)^t} \\
& + \sum_o \sum_c \sum_t \frac{(DIS_{oct} \times CYF_t^{\pm} + CZF_t^{\pm} + CCF_{oct}^{\pm})X_{oct}^{\pm}}{(1+q)^t} \quad (2.3.4a)
\end{aligned}$$

$$\begin{aligned}
MinZ2^{\pm} = & \sum_o \sum_l \sum_t \frac{(QSHE^{\pm} \times CHEN^{\pm} + QTAN^{\pm} \times CTMQ^{\pm}) \times X_{olt}^{\pm}}{(1+q)^t} \\
& + \sum_o \sum_i \sum_t \frac{(QFEN^{\pm} \times CFEN^{\pm} + QFEI^{\pm} \times CFEI^{\pm}) \times X_{oit}^{\pm}}{(1+q)^t} \\
& + \sum_o \sum_c \sum_t \frac{QDUI^{\pm} \times CDUI^{\pm} \times X_{oct}^{\pm}}{(1+q)^t} \quad (2.3.4b)
\end{aligned}$$

where in Z1 represents system costs objective and Z2 environmental impact objective; and  $\pm$  indicates the maximum and minimum values.  $O$  stands for the origin of waste, including transfer stations and various treatment facilities;  $t$  represents time (years),  $r$ , recycle stations,  $l$ , landfill,  $i$ : incineration plants and  $c$ , composting plants.  $DIS$  stands for distance of transportation (km),  $q$ , discount rate, and  $CYF^{\pm}$  waste transport costs per unit of distance and weight (¥/km, t).  $X^{\pm}$  describes the weight of waste (t/d),  $CZF^{\pm}$ , transfer costs (¥/t), and  $CRF^{\pm}$ ,  $CLF^{\pm}$ , and  $CIF^{\pm}$  indicate unit costs for recycling, landfill and incineration respectively.  $QSHE^{\pm}$  means the quantity of leachate produced per unit of waste (t/t) and  $CHEN^{\pm}$ , leachate treatment costs.  $QTAN^{\pm}$  means the quantity of landfill gas produced per unit of waste (t/t) and  $CTMQ^{\pm}$ , landfill gas treatment costs (¥/t).  $QFEN^{\pm}$  means the quantity of exhaust gas produced from incineration per unit of waste (t/t) and  $CFEN^{\pm}$ , exhaust gas treatment costs (¥/t).  $QDUI^{\pm}$  means the quantity of odor produced from composting per unit of waste (t/t);  $CDUI^{\pm}$ , odor treatment costs (¥/t).  $QFEI^{\pm}$  means the quantity of ash generated per unit of waste (t/t) and  $CFEI^{\pm}$ , ash treatment costs (¥/t).

## (2) Constraints

### (i) Mass balance



- a. Total Amount of Solid Waste = Forecasted Amount of Solid Waste Generation:

$$\sum_r X_{art}^{\pm} + \sum_l X_{alt}^{\pm} + \sum_i X_{ait}^{\pm} + \sum_c X_{act}^{\pm} = Q_t^{\pm} \quad (2.3.5a)$$

where  $a$  represents transfer stations and  $Q_t^{\pm}$  forecasted MSW in year  $t$ ;

- b. Total Amount of Solid Waste from Origin of Waste  $\geq$  Forecasted Amount of Solid Waste Generation;

$$\sum_r X_{ort}^{\pm} + \sum_l X_{olt}^{\pm} + \sum_i X_{oit}^{\pm} + \sum_c X_{oct}^{\pm} \geq Q_t^{\pm} \quad (2.3.5b)$$

- c. Amount of Waste Destined from Transfer Stations for Landfill + Amount of Waste Destined from Treatment Stations for Landfill = Total Amount of Waste Destined for Landfill;

$$\sum_a X_{alt}^{\pm} + \sum_r X_{rlt}^{\pm} + \sum_c X_{clt}^{\pm} + \sum_i X_{ilt}^{\pm} = \sum_o X_{olt}^{\pm} \quad (2.3.5c)$$

- d. Amount of Waste Destined from Transfer Stations for Incineration Plants + Amount of Waste Destined from Recycle Stations for Incineration Plants = Total Amount of Waste Destined for Incineration Plants;

$$\sum_a X_{ait}^{\pm} + \sum_r X_{rit}^{\pm} = \sum_o X_{oit}^{\pm} \quad (2.3.5d)$$

- e. Waste that has been treated can no longer return to the recycle stations:

$$\sum_l X_{lrt}^{\pm} = 0 \quad (2.3.5e)$$

$$\sum_i X_{irt}^{\pm} = 0 \quad (2.3.5d)$$

$$\sum_c X_{crt}^{\pm} = 0 \quad (2.3.5g)$$

- f. Waste that has been treated can no longer return to the composting plants:

$$\sum_l X_{lct}^{\pm} = 0 \quad (2.3.5h)$$

$$\sum_i X_{ict}^{\pm} = 0 \quad (2.3.5i)$$

$$\sum_r X_{rct}^{\pm} = 0 \quad (2.3.5j)$$

(ii) Ash rate

$$\sum_i X_{ait}^{\pm} \times \alpha = \sum_l X_{ilt}^{\pm} \quad (2.3.6a)$$

$$\sum_c X_{ait}^{\pm} \times \beta = \sum_l X_{clt}^{\pm} \quad (2.3.6b)$$

$$\sum_r X_{art}^{\pm} \times \gamma = \sum_l X_{rlt}^{\pm} + \sum_i X_{rit}^{\pm} \quad (2.3.6c)$$

where  $\alpha$  represents the residue rate in waste incineration plants,  $\beta$  residue rate in composting plants, and  $\gamma$  residue rate in recycle stations.

(iii) Maximum processing capacity

$$\sum_i X_{oit}^{\pm} \leq CAXI \quad (2.3.7a)$$

$$\sum_c X_{oct}^{\pm} \leq CAXC \quad (2.3.7b)$$

$$\sum_l X_{olt}^{\pm} \leq CAXL \quad (2.3.7c)$$

$$\sum_r X_{ort}^{\pm} \leq CAXR \quad (2.3.7d)$$

$$\sum_a X_{at}^{\pm} \leq CAXA \quad (2.3.7e)$$

where  $CAXI$ ,  $CAXC$ ,  $CAXA$ ,  $CAXL$ , and  $CAXA$  refer to the maximum processing capacity (t/d) of incineration plants, composting plants, landfills, and transfer stations respectively.

## (iv) Minimum processing capacity

$$\sum_i X_{oit}^{\pm} \geq CANI \quad (2.3.8a)$$

$$\sum_c X_{oct}^{\pm} \geq CANC \quad (2.3.8b)$$

$$\sum_r X_{ort}^{\pm} \geq CANR \quad (2.3.8c)$$

$$\sum_a X_{at}^{\pm} \geq CANA \quad (2.3.8d)$$

$$\sum_t X_{ot}^{\pm} \geq CAMQ \quad (2.3.8e)$$

$$\sum_l X_{olt}^{\pm} \geq CDMT \quad (2.3.8f)$$

where *CANI*, *CANC*, *CANL*, *CANA*, and *CAMQ* refer to the minimum processing capacity (t/d) of incineration plants, composting plants, landfills, transfer stations and recycle stations respectively. Among MSW, such substances as clinkers, bricks, ceramics and residues after treatment must be buried. *CDMT* stands for the minimum amount of landfill (t/d) (Table 2.2).

## (v) Usable components

$$\sum_i X_{oit}^{\pm} \leq \omega_1 \cdot QBI^{\pm} \quad (2.3.9a)$$

$$\sum_c X_{oit}^{\pm} \geq \omega_2 QBC^{\pm} \quad (2.3.9b)$$

$$\sum_r X_{ort}^{\pm} \geq \omega_3 QBR^{\pm} \quad (2.3.9c)$$

**Table 2.2** Waste components and applicable treatment methods

Treatment facilities	Type of waste
Landfill	All
Composting	Food waste, plants
Incineration	Food waste, plants, paper, plastics, rubber, textiles, wood and bamboo
Recycling	Metal, glass, paper, plastics, rubber, textiles, wood and bamboo

MSW has complicated and diverse components which pose constraints to disposal methods. Improper operations in waste sorting or disposal hinder ideal waste disposal, resulting in utilization factor constraints. In the above formulas,  $\omega_1$ ,  $\omega_2$ , and  $\omega_3$  represent the utilization factor of incineration, composting, and recycling respectively. In China, Guo Guangzhai et al. concluded the utilization factor for composting and recycling is 90 % based on the MSW research to Shanghai.

(vi) Capacity of treatment facilities

Solid waste treatment inevitably produces secondary pollution. In the multi-objective optimization model, the amount of secondary pollution should be no more than the treatment capacity of facilities to meet the emission standards.

$$QSHE^{\pm} \cdot X_{olt}^{\pm} \leq TAXS \quad (2.3.10a)$$

$$QFEN^{\pm} \cdot X_{oit}^{\pm} \leq TAXE \quad (2.3.10b)$$

$$QDUI^{\pm} \cdot X_{oct}^{\pm} \leq TAXD^{\pm} \quad (2.3.10c)$$

$$QFEI^{\pm} \cdot X_{oit}^{\pm} \leq TAXI \quad (2.3.10d)$$

where  $TAXS$ ,  $TAXE$ ,  $TAXD$ , and  $TAXI$  represent daily processing capacity (t/d) of treatment facilities for leachate, exhaust gas from incineration, composting odor, and ash respectively.

(vii) Non-negative constraints

Non-negative means all the values are greater than zero. The amount of waste out from transfer stations and from treatment plants should meet the non-negative requirement. In other words,  $X_{oit}^{\pm}$ ,  $X_{olt}^{\pm}$ ,  $X_{oct}^{\pm}$ ,  $X_{ort}^{\pm}$ ,  $X_{ait}^{\pm}$ ,  $X_{alt}^{\pm}$ ,  $X_{act}^{\pm}$ ,  $X_{art}^{\pm}$ ,  $X_{ilt}^{\pm}$ ,  $X_{clt}^{\pm}$ ,  $X_{rlt}^{\pm}$ ,  $X_{rit}^{\pm}$ , and  $X_{cit}^{\pm} \geq 0$ .

(3) Basic data collection, parameter identification, and optimization calculation

The results of optimization model are closely related to the authenticity of parameters. Applicable methods for data acquisition include on-site survey, literature review, and expert consultation. The data obtained by various means should be verified to ensure actual effectiveness.

In the calculation for optimization, it is necessary to change the multi-objective uncertain model into single-objective, deterministic model before solving the formula on the basis of uniform unit and consistent symbol. The model is calculated using LINGO, a simple tool to solve linear and nonlinear optimization problems. Particularly, the language integrated with LINGO can easily express problems and the efficient solver can realize fast solution and effective analysis of the results.

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