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# Estimation on hazardous characteristics of the components from linear type of end-of-life light-emitting diode lamps

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## Abstract

The supply of light-emitting diode (LED) lamps has been expanding as lighting devices to replace fluorescent lamps. Accordingly, it is expected that a large amount of end-of-life LED lamps will be generated. Among various types of LED lamps, liner LED lamps are generally used. Since linear LED lamps have been reported to use hazardous materials such as As and Pb, the hazardous characteristics of end-of-life LED lamps were estimated. To verify the hazardous characteristics of end-of-life linear LED lamps, leaching tests such as Korea Extraction Test (KET) and Toxicity Characteristics Leaching Procedure (TCLP) were carried out for the overall mixture and the each component of end-of-life linear LED lamps. The linear LED lamp is generally composed of cover, frame, LED, the driver and others. The portions of LED and the driver in linear LED lamp are only about 1% and 10%, respectively. End-of-life linear LED lamp can be non-hazardous waste because leaching concentrations of heavy metals in the overall mixture of end-of-life linear LED lamp were lower than the regulatory level. Since leaching concentrations of As, Pb and Cu in LED and the driver were higher than the regulatory level, however, LED and the driver can be classified as the hazardous waste.


**Keywords** LED · Hazardous characteristic · Korea extraction test (KET) · Toxicity characteristics leaching procedure (TCLP)

## Introduction

Recently, many developed countries are implementing policies to expand the supply of LED lamps in response to climate change and the improvement of energy efficiency [1–3]. Both the Basel Convention and the Minamata Convention have been managed a global treaty for mercury to protect human health and the environment from the adverse effects of mercury [4, 5]. In the field of lighting equipment, the supply and the use of light-emitting diode (LED) lamp have been expanding with highly efficiency lighting equipment because fluorescent lamps contained mercury [6–8]. In Korea (Republic of), the supply of LED lamps are being promoted by the plan of LED lamp 2060s in Ministry of Trade, Industry and Energy (MOTIE). The policy aimed at 60% of LED lamp supply in Korea (Republic of) by 2020 [9]. The policy actively promoted for the supply of LED lamps but there was lack of the statistics on the use and the import of LED lamps. According to the Ministry of Environment (MoE), the shipment amount of fluorescent lamps decreased from 149,306 thousand in 2013 to 122,551 thousand in 2015 [10, 11]. It was estimated that fluorescent lamps have replaced with LED lamps by the difference of shipment amount.

To reduce energy usage by lighting equipment in Korea, the installation status of lighting equipment was investigated by Korea Energy Agency [12]. In 2013, the number of installation of lighting equipment in industrial, household and commercial filed was 657,808 thousand for fluorescent lamp, 148,938 thousand for LED lamp, 31,615 thousand for High-Intensity Discharge lamp (HID lamp) and 92,488 thousand for other lighting equipment. According to a recent investigation by Ministry of Environment in Korea, the LED lamp was 30,000 thousand for production, 34,000 thousand for import, 26,000 thousand for export in 2017 [13]. In Korea, the regulation for the management of end-of-life fluorescent

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lamp has been enforced by extended producer responsibility (EPR) but there is no regulation for the management of end-of-life LED lamps. The ratio of end-of-life LED lamps discharged into the collection box of end-of-life fluorescent lamp was estimated to be about 4.3% [13].

Due to the LED lamp supply policies, recently, LED lamps have discharged from household and industries as wastes, and the generation amount of end-of-life LED lamps is anticipated gradually to increase. Since LED lamps can be turned up by various types and specifications as shown in Fig. 1, it is difficult to control end-of-life LED lamps environmentally and properly. Since LED lamps should be used under the conditions of use of conventional fluorescent lamps, linear type, recessed type and mirror reflect type are often used. The special types include magnet type, mobile type, special color-emitting type, etc. Among them, linear LED lamp is most commonly used because it can replace fluorescent lamps that are traditionally used [14]. The linear LED lamps are generally composed of frame, cover, LED, LED board, the driver, etc. The LED, a key component to emit light, is composed of various materials such as AlGaAs, GaAsP or InGaAlP, InGaN, etc. and the diver contains Pb [14–18]. According to the Risk Assessment Information System (RAIS) database, the acute lethal dose of inorganic arsenic to humans was estimated to be about 0.6 mg/kg/day [19, 20]. However, there are few studies on the physical composition and hazardous characteristics of LED lamps due to various types of LED lamps.

Lim et al. has evaluated the toxicity potential of LED lamps according to the color, and reported that Pb content of red LEDs may be highly toxicity potential at 8103 mg/kg [15]. Lim et al. found that the copper content in the Bulb type LED is 31,600 mg/kg, which is a potential hazard [16]. Machacek et al. evaluated the potential of supply of rare earth metals by the recycling of lamps such as compact fluorescent lamps, linear fluorescent lamps and LED lamps [21]. They found that the supply of rare earth metals from the recycling of lamps can help to reduce the primary production of rare earth metals [21]. Zhan et al. suggested the recycling technology for recovering rare earth metals such as Ga and In [22]. Fang et al. evaluated the recyclability of end-of-life LED lamps using factors such as mechanical processing cost and environmental impact including toxic material content [23]. They found that green LEDs have a high potential for metal recycling, and blue LEDs have a low potential for recycling. These studies have focused on material recovery from LED lamps and little research has been done on hazardous characteristics by toxic materials in end-of-life LED lamps.

Therefore, it is necessary to estimate the hazardous characteristics for the overall mixture and the components of end-of-life liner LED lamps by leaching tests such as Korea Extraction Test (KET) and Toxicity Characteristics Leaching Procedure (TCLP). To estimate the components of linear LED lamp, end-of-life liner LED lamps were separated into cover, frame, LED, the driver and others. And leaching concentration of heavy metals in the overall mixture and the component of end-of-life linear LED lamp verified whether end-of-life linear LED lamp is hazardous waste or not.

## Materials and methods

### Materials

End-of-life linear LED lamps were collected from remodeling and demolition of commercial buildings and households. The number of collected end-of-life LED lamps was mainly classified as 12 W, 15 W and 20 W. Therefore, end-of-life linear LED lamps such as 12 W (sample A), 15 W (sample B) and 20 W (sample C) from different manufactures are used as experimental samples. The structure of

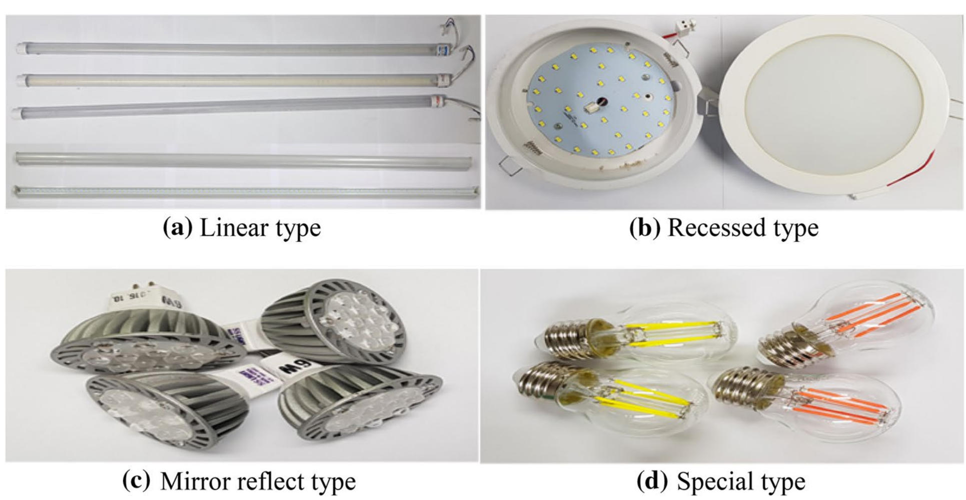
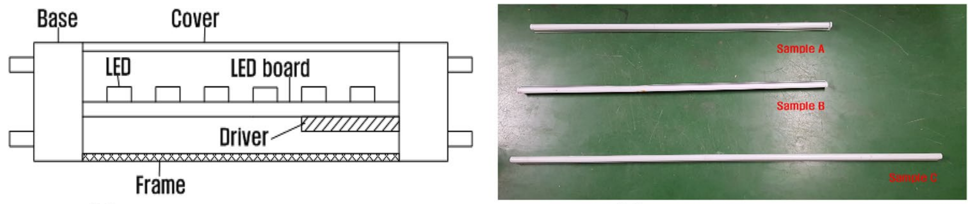



**Fig. 1** The various types of LED lamps



(a) Schematic diagram of sample (b) Picture of sample

**Fig. 2** The schematic diagram and picture of sample

**Table 1** Specification of sample type of LED lamp

| Type | Sample A | Sample B | Sample C |
|---|---|---|---|
| Rated voltage | 220 V, 60 Hz | 220 V, 60 Hz | 220 V, 60 Hz |
| Electric power (W) | 12 | 15 | 20 |
| Diameter (mm) | 23 | 23 | 23 |
| Length (mm) | 872 | 872 | 1171 |
| Weight (g) | 155.38 | 164.53 | 215.67 |

end-of-life linear LED lamps is shown in Fig. 2. The outside of end-of-life linear LED lamps consists of cover, frame and base. LED is attached to LED board and the driver is located on the opposite edge of LED. In end-of-life linear LED lamps, the driver, which is a device to regulate the supply of power and current, is similar to the ballast in Compact Fluorescent lamp (CFL). The specification of LED lamp sample is shown in Table 1. The samples of end-of-life linear LED lamps have the same diameter in 23 mm and the same rated voltage in 220 V, 60 Hz even though the samples have different electric power. The weight of the samples was measured as 157.41 g in sample A, 165.74 g in sample B and 210.51 g in sample C, respectively. Among the components of end-of-life linear LED lamps, the portion of the driver and LED in end-of-life linear LED was about 10% and about 1%, respectively. To conduct the leaching test for LED only, 190 pieces of sample A, 185 pieces of sample B and 120 pieces of sample C were used to prepare the amount of a LED sample, 100 g. End-of-life linear LED lamps used as samples for the overall mixture were manufactured in China between 2014 to 2015. The samples used as each component of end-of-life linear LED lamps were produced between 2011 and 2015.

### Experimental method

To estimate the portion of end-of-life linear LED lamps, each component of the LED lamps was separated manually. To verify the hazardous characteristics of end-of-life linear LED lamps, leaching tests such as Korea Extraction Test (KET) and Toxicity Characteristic Leaching Procedure (TCLP) were carried out. In the procedure of KET, the sample was crushed to be less than 5.0 mm and the pH of the solvent was controlled between 5.8 and 6.3. The solid–liquid ratio of 1:10 (100 g of the sample and 1000 ml of the solvent) was set and shaken for 6 h and then the supernatant was separated with a glass fiber filter of 1.0 µm [24]. In the procedure of TCLP, the sample was prepared in less than 9.5 mm. There are two kinds of solvents used in TCLP such as fluid #1 (pH $4.93 \pm 0.05$) and fluid #2 (pH $2.88 \pm 0.05$). In this experiment, fluid #1 was used as a solvent. The solid–liquid ratio of 1:20 (100 g of the sample and 2000 ml of the solvent) was set and shaken for 18 h, and then the supernatant was separated with a glass fiber filter of 0.6–0.8 µm [25]. In KET, waste is used to verify hazardous matter specified under the Korean Waste Control Act [26]. In TCLP, waste may satisfy with hazardous characteristics in 40CFR (Code of Federal Regulations) Part 26 under Resource Conservation and Recovery Act (RCRA) [27]. The leaching tests were carried out in two ways. One way of leaching test was applied to each component of end-of-life linear LED lamp. The other way was used to the overall mixture of end-of-life linear LED lamp. The components of end-of-life linear LED lamp were LED, the driver and others. The leaching test of the overall mixture of end-of-life linear LED lamps was carried out for the mixture of all components. After carrying out KET and TCLP for LED, the driver and others, Atomic Absorption Spectrometer (PG-990, PG industry) was applied through the Korean Standard Method (ES 06400.1) to analyze the leaching concentration of heavy metals such as Cu, $Cr^{6+}$, As, Pb, Cd, and Hg in leaching solution. Measurements were conducted 3 times for every leaching solution to estimate the average value of the leaching concentration.

## Results and discussion

### Major components of end-of-life linear LED lamps

The portion of each component of LED lamp samples is shown in Fig. 3. Among the components, the cover and base are made of plastic, and the frame and LED board are made of aluminum. The others are mixture of binders, metals and some residual fragment from separated procedure of end-of-life linear LED lamp. The weight and portion of each components from the samples A, B, and C are shown in Table 2. Among the components, the frame showed the largest percentage, followed by cover, LED board and base. Plastics such as cover

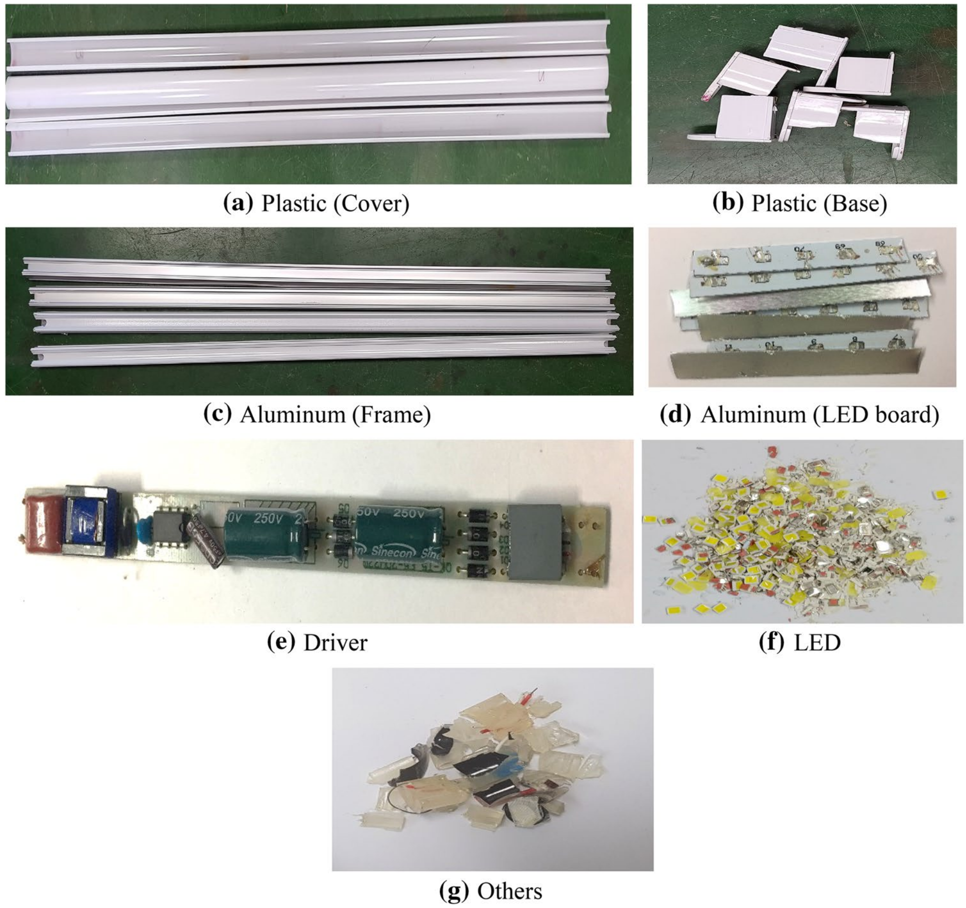



**Fig. 3** The separated components from end-of-life linear LED lamps

**Table 2** Major component of end-of-life linear LED lamps

| Type | Sample A | | Sample B | | Sample C | |
|---|---|---|---|---|---|---|
| | Weight (g) | Ratio (%) | Weight (g) | Ratio (%) | Weight (g) | Ratio (%) |
| Plastic | | | | | | |
| Cover | 19.66 | 12.65 | 22.22 | 13.51 | 31.15 | 14.44 |
| Base | 9.06 | 5.83 | 10.84 | 6.59 | 9.77 | 4.53 |
| Aluminum | | | | | | |
| Frame | 75.26 | 48.44 | 67.10 | 40.78 | 92.94 | 43.09 |
| LED board | 16.69 | 10.74 | 20.66 | 12.55 | 26.68 | 12.37 |
| LED | 1.62 | 1.04 | 1.64 | 1.00 | 2.50 | 1.16 |
| Driver | 13.53 | 8.71 | 16.15 | 9.82 | 24.22 | 11.23 |
| Others | 19.57 | 12.59 | 25.93 | 15.76 | 28.41 | 13.17 |
| Total | 155.38 | 100.00 | 164.53 | 100.00 | 215.67 | 100.00 |

and base and aluminum such as the frame and LED board were separated to recycle from end-of-life linear LED lamps. The amount of plastic and aluminum accounts for about 20% and about 56%, respectively.

## Leaching concentration of the overall mixture of end-of-life linear LED lamp

To evaluate leaching concentration of end-of-life linear LED lamps, the 6 heavy metals such as As, Pb, Cu, Cd, $Cr^{6+}$, and Hg were adopted because they are regulated as hazardous wastes under Waste Control Act in Korea and RCRA in USA. The results of leaching concentration for the overall mixture of end-of-life linear LED lamps by KET and TCLP are shown in Table 3.

The leaching concentrations of heavy metals in KET were satisfied with the regulatory level of hazardous wastes under Waste Control Act. Unlike in TCLP, the leaching concentration of Cu is regulated by 3.0 mg/L in KET. Choi et al. reported potential hazardousness of Cu in LED itself [14]. However, the leaching concentration of Cu of the overall mixture of end-of-life LED in KET was less than 0.6 mg/L, which was much lower than the regulatory level in Korea. In TCLP, the leaching concentrations of As and Cd were slightly higher than those from the result in KET. However, the leaching concentration of all heavy metals does not exceed the regulatory level. From all experimental results, the leaching concentration in TCLP was higher than that in KET because the pH of the solvent used in TCLP is lower than that used in KET.

Lim et al. estimated that leaching concentration of heavy metals using bulb type LED lamp (7 W) by TCLP was measured independently for ground parts (less than 2 mm of particle size) and underground parts (less than 9.5 mm of particle size) to take into account the size difference [16]. As the result of TCLP for underground parts, Cu was analyzed as 0.027 mg/L and other heavy metals were not detected. Especially, Pb for ground parts in TCLP was analyzed as 44.4 mg/L, which exceeded over 8 times of regulatory level. Kumar et al. conducted TCLP using end-of-life LED lamps crushed to 9.5 mm or less [28]. Pb was detected in the leaching solution from crushed LED lamps, but the leaching concentration of Pb was satisfied with the regulatory level in TCLP. Lim et al. and Kumar et al. showed that the hazardous characteristics of end-of-life LED lamps depended on the particle size of components [16, 28]. Therefore, it was estimated that the content of heavy metals in the overall mixture of end-of-life linear LED lamp was very small.

From the results of leaching test for the overall mixture of end-of-life linear LED lamp, the leaching concentrations of heavy metals in TCLP are generally higher than those in KET. The leaching concentrations of heavy metals in the overall mixture from end-of-life linear LED lamps were satisfied with the regulatory level in KET and TCLP. Hence, the overall mixture of end-of-life linear LED lamp was verified to be non-hazardous waste.

## Leaching concentration of each components

The results of leaching concentration of LED and the driver from end-of-life linear LED lamps using KET and TCLP are shown in Table 4. In KET, As, Pb and Cu were detected from LED itself, and Pb, Cu and Cd were detected from the driver. With respect to LED, the leaching concentration of As and Pb in KET exceeded the regulatory level and that of Cu was satisfied with the regulatory level in all samples. For the driver, the leaching concentration of Pb and Cu in KET was relatively high because of solder materials and copper wire in the LED samples. $Cr^{6+}$ and Hg in leaching solution were not detected in LED and the driver. In KET, the detected heavy metal from others is Cu but the leaching concentration of Cu in others is satisfied with the regulatory level.

The results of the leaching concentration of As and Pb in TCLP exceeded the regulatory level for all LED samples. From the result of KET and TCLP, the concentration of As and Pb in leaching solution of LED samples exceeded the regulatory level and the concentration of Pb in leaching

**Table 3** Leaching concentration of overall mixture of end-of-life linear LED lamp by KET and TCLP (mg/L)

| Type | As | Pb | Cu | Cd | $Cr^{6+}$ | Hg |
|---|---|---|---|---|---|---|
| KET | | | | | | |
| Regulatory level | 1.5 | 3.0 | 3.0 | 0.3 | 1.5 | 0.005 |
| Sample A | N.D | 0.849 | 0.437 | N.D | N.D | N.D |
| Sample B | N.D | 0.751 | 0.431 | N.D | N.D | N.D |
| Sample C | N.D | 0.938 | 0.580 | N.D | N.D | N.D |
| TCLP | | | | | | |
| Regulatory level | 3.0 | 5.0 | – | 1.0 | 5.0 | 0.2 |
| Sample A | N.D | 1.440 | 0.925 | 0.023 | N.D | N.D |
| Sample B | 0.083 | 1.185 | 1.039 | 0.021 | N.D | N.D |
| Sample C | 0.095 | 1.689 | 1.249 | 0.024 | N.D | N.D |
| Bulb type [16] | | | | | | |
| TCLP (ground parts) | N.D | 44.4 | 3.1 | N.D | N.D | N.D |
| TCLP (underground parts) | N.D | N.D | 0.027 | N.D | N.D | N.D |
| TCLP (crushed LED lamp) [28] | N.D | 0.95 | N.D | N.D | N.D (total Cr) | N.D |

*N.D* not detected

**Table 4** Leaching concentration of each components by KET and TCLP (mg/L)

| Type | As | Pb | Cu | Cd | $Cr^{6+}$ | Hg |
|---|---|---|---|---|---|---|
| KET | | | | | | |
| Regulatory level | 1.5 | 3.0 | 3.0 | 0.3 | 1.5 | 0.005 |
| LED | | | | | | |
| Sample A | 3.110 | 3.156 | 0.003 | N.D | N.D | N.D |
| Sample B | 3.421 | 3.521 | 0.004 | N.D | N.D | N.D |
| Sample C | 3.060 | 3.409 | 0.005 | N.D | N.D | N.D |
| Driver | | | | | | |
| Sample A | N.D | 9.373 | 5.018 | 0.072 | N.D | N.D |
| Sample B | N.D | 8.842 | 5.102 | 0.077 | N.D | N.D |
| Sample C | N.D | 8.233 | 4.950 | 0.082 | N.D | N.D |
| Others | | | | | | |
| Sample A | N.D | N.D | 0.019 | N.D | N.D | N.D |
| Sample B | N.D | N.D | 0.009 | N.D | N.D | N.D |
| Sample C | N.D | N.D | 0.013 | N.D | N.D | N.D |
| TCLP | | | | | | |
| Regulatory level | 3.0 | 5.0 | – | 1.0 | 5.0 | 0.2 |
| LED | | | | | | |
| Sample A | 7.038 | 5.615 | 0.020 | 0.208 | N.D | N.D |
| Sample B | 8.701 | 6.207 | 0.037 | 0.212 | N.D | N.D |
| Sample C | 8.337 | 5.798 | 0.055 | 0.206 | N.D | N.D |
| Driver | | | | | | |
| Sample A | N.D | 15.858 | 10.621 | 0.214 | 0.041 | N.D |
| Sample B | N.D | 13.571 | 10.920 | 0.215 | 0.055 | N.D |
| Sample C | N.D | 12.941 | 11.925 | 0.217 | 0.069 | N.D |
| Others | | | | | | |
| Sample A | N.D | 0.084 | 0.032 | 0.005 | N.D | N.D |
| Sample B | N.D | 0.058 | 0.042 | 0.007 | N.D | N.D |
| Sample C | N.D | 0.062 | 0.056 | 0.007 | N.D | N.D |

*N.D* not detected

solution of the driver was not satisfied with the regulatory level. The heavy metals such as Pb, Cu and Cd were detected from others in TCLP, and the leaching concentration was not exceeded the regulatory level. Therefore, only LED and the driver were classified to be hazardous wastes. Since the portion of both LED and the driver is only about 11%, however, the hazardous effect of LED and the driver to the overall mixture of end-of-life linear LED lamp can be limited.

Various researches have been reported on the hazardousness of As and Pb in LED lamps [15, 29, 30]. The reason why the detection of As was reported in LED lamps was that linear LED lamps have used the materials containing As such as AlGaAs and GaAsP. In this study, however, it was found that the overall mixture of end-of-life linear LED lamp can be non-hazardous waste even though the leaching concentration of LED and the driver were not satisfied with the regulatory level. Rahman et al. suggested the recycling processes of end-of-life LED lamps for recycling of plastics and aluminum and recovery of rare earth metals from LED [31]. In the suggested recycling processes of end-of-life LED lamps, LED and the driver can be considered as hazardous wastes. The LED was reported to contain valuable material such as Au, Ag, Ti and Y [14, 31–34]. Therefore, it is desirable that valuable materials such as Au, Ag and Ti in end-of-life linear LED lamps should be utilized through appropriate treatment of hazardous materials such as As, Pb and Cu.

## Conclusions

To estimate the hazardous characteristics for the overall mixture and the components from end-of-life linear LED lamps, leaching tests such as KET and TCLP were carried out. The major components of end-of-life linear LED lamps are cover, base, frame, LED board, LED, the drive and others. Among the materials, the important parts in end-of-life linear LED lamps were LED and driver, which can show hazardous characteristics. The portion of LED and the driver is about 1% and about 10%, respectively. From the results of leaching test, metal concentrations in leaching solutions in TCLP are generally higher than those in KET. The leaching concentrations of heavy metals in the overall mixture from end-of-life linear LED lamps were satisfied with the regulatory level in KET and TCLP. The leaching concentrations in LED and the driver in KET and TCLP were satisfied with the regulatory level except the leaching concentration of As, Cu and Pb. The leaching concentration of As in LED was not satisfied with the regulatory level because materials containing As such as AlGaAs and GaAsP were used in LED. For the driver, the leaching concentrations of Pb and Cu by KET and TCLP were relatively high because the solder material and Cu wire were included in the driver. As a result, the overall mixture of end-of-life linear LED lamps can be classified as non-hazardous waste. However, LED and the driver as components from end-of-life linear LED lamps can be classified as hazardous wastes.

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