Evaluation on the benefit of practically operating reverse osmosis system in the factory: taking the recycle of KI solution and water of the screen polarizing plate as an example
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ABSTRACT
In recent years, with the advocacy of circular economy and the rising awareness of environmental protection, energy saving, water saving and carbon reduction have become an important topic for discussion today. The high-tech semiconductor, photoelectric, solar and other electronic industries involve high energy and water consumption. In addition to responding to the energy saving, water saving and carbon reduction, one of the main purposes of this system development is to reduce the use of materials and make the process chemicals reusable. In the practical factory operation, a large amount of water is used in the polarization process, and the wastewater generated in etching and pickling is discharged continuously. In order to recycle the water discharging from the manufacturing process, the reverse osmosis membrane system (RO membrane system) is often used for wastewater recycling. In this study, the KI waste liquid discharging from the process of a polarizing plate factory was concentrated with anti-fouling RO membrane; the quantity and arrangement of RO system membranes were simulated and designed with software; and the results, such as water volumes and pressures of inflow and outflow water for the membrane, changes of membrane pressure difference (ΔP), changes of permeating water quality, chemical cleaning frequency and water collection time, were discussed and the optimal parameters of RO membrane, such as the best water collection volume and time, chemical cleaning frequency, best concentration, time and temperature matching with cleaning in process (CIP) were inferred so as to improve the stability of RO membrane system, enable RO permeating water to enter the water purifying system for reuse, reduce the treatment cost of wastewater recycle and improve the permeating water output efficiency of treatment equipment, which accommodating effective utilization of water resources and economic benefits, leading to sustainable development of the industry.

Key words | polarization process, RO, RO membrane, wastewater recycle

HIGHLIGHTS
- RO membrane system runs stably, the concentration of KI will be relatively stable and the recovered water quality can be purer.
About US$ 670,000 is needed for wastewater treatment and water pollution fees, while US$ 560,000 can be saved per year from the benefits of the recycle technology according to this study, for which the investment can be recovered in about 1.14 years.

INTRODUCTION

With the advancement of industrial production technology, the industrial process is also rapidly improved and the characteristics of pollutants in the wastewater system are constantly changing. The scarcity of water resources is increasingly affecting the global economic development and ecological environment. In order to improve treatment efficiency, reduce land use and water consumption cost, explore the potential advantages and feasibility of the system to recycle wastewater, reduce the concentration of pollutants and reduce the impact on the ecological environment.

In the related studies of RO membrane technology (Chang 2000; Benito & Ruiz 2002; Ozaki et al. 2002; Hsu 2004; Chang & Ch’en 2005; Lin 2005; Hsu et al. 2018; Zheng et al. 2018), scholars also pointed out that RO membrane was suitable for the treatment of metal processing wastewater (Benito & Ruiz 2002; Ozaki et al. 2002). It could be used to purify the rinsing water of electroplating layer and concentrate the plating metal ion so that the water can be used repeatedly in electroplating bath, which brings significant economic benefits (Hsu et al. 2018; Xu, 2018). Therefore, this study is to evaluate the benefit of recycling the KI solution and water from a screen polarizing plate factory with the RO system.

With the increasing shortage of water resources in Taiwan, the recycle cost of RO water is about US$ 0.83/t, which can reduce the water pollution control fee and wastewater treatment fee as required by the administrative bureau by US$ 1/t. For example: Assuming that a polarizing plate factory recycles wastewater of 250 cubic meter per day (CMD), it can save annually US$ 168,630; if the 2 CMD KI solution recycled per day (about US$ 5/L) is added, the annual saving will be US$ 3,650,000; after deducting the operating cost of US$ 109,000, the annual saving will be US$ 3,709,579, which indicates recycle benefit is very remarkable.

Therefore, in this study, the benefits of operating RO system for the purpose of KI solution and water recycle in a screen polarizing plate factory are evaluated, and the key points and directions are discussed are as follows:

I. analyzing water quality of waste liquid from the polarizing plate manufacturing process;
II. discussing the mechanism of blocking and scaling of RO membrane;
III. comparing the operations between RO membrane for water purification and anti-fouling RO membrane for water recycle and
IV. overall benefits of recycling both KI solution and water from the polarizing plate manufacturing process.

STUDY METHODS

In this study, the water quality of the polarizing plate factory was analyzed and tested first so as to understand the components contained in the water, and then, the water quality and various influencing factors were input. The quantity and arrangement of RO system membranes were simulated and designed with software, and based on the results, such as water volumes and pressures of inflow and outflow water for the membrane, changes of membrane pressure difference (ΔP), changes of permeating water quality, chemical cleaning frequency and water collection time, and the optimal parameters of the RO membrane, such as the best water collection volume and time, chemical cleaning frequency, best concentration, time and temperature matching with cleaning in process (CIP), were inferred. Based on this, the operating cost and recycle period were derived, the optimal parameters were tested and the benefits of the study were evaluated by integrating the above
conditions. The schematic diagram of the study methods is shown in Figure 1.

**Test equipment and materials**

In this test, the membrane developed by H Company (Table 1) and the RO membrane produced by H Company were used. The membrane was made of polyamides and had a daily permeating water flow rate per membrane of 41.6 CMD; a desalination rate of 99.7% (minimum of 99.5%); a structure of low pollution spiral winding; a membrane area of 400 ft² (37.1 m²); a water feeding pipe of 34 Mil (0.864 mm); a maximum resistance to residual chlorine concentration of <0.1 PPM; a maximum pressure resistance of 600 psig (4.16 MPa); a maximum operating temperature of 113 °F (45 °C); a continuous pH range (chemical cleaning) of 2–10 (1–12); a maximum feeding water turbidity of 1.0 NTU; a maximum feeding water supply SDI (15 min) of 5 and a maximum inflow 75 GPM (17.0 m³/h).

In order to avoid the interference of other ions, the ultra-pure water was used as the reagent water during the experiment process, and the reagent types used are as follows:

1. Sodium hydroxide (NaOH): Merck, 99.6%
2. Sodium carbonate (Na₂CO₃): Ferak, 99.5%
3. Hydrochloric acid (HCl): Merck, 99.5%
4. EDTA tetrasodium salt: Daojiu, 99.5%
5. Sodium hypochlorite (NaOCL): MERCK, 50%
6. Sodium bicarbonate (NaHCO₃): Ferak, 99.5%
7. Acid (H₂SO₄): Merck, 95–97%
8. Phosphoric acid (H₃PO₄): Merck, 85%

**General principles for the design of RO membrane system**

The complete RO system setup was mainly composed of four parts, including pretreatment, RO host (membrane filtration), posttreatment and system cleaning.

The flowchart of the RO system of this study is shown in Figure 2 and Table 2 shows the RO system units.

The design of RO membrane filtration system in the RO main machine (membrane filtration) included the membrane module, pressure vessel arrangement, high-pressure pump, pipeline, instruments and meters, etc. The general principles of its design were to reduce the operating pressure of the system as much as possible, save the cost of membrane module, maintain the long-term stability of the system, reduce its cleaning and maintenance costs and achieve the increase of permeating water flow rate and KI recycle rate. The most significant factor in the design of RO membrane system was the fouling tendency of feeding water. The fouling of membrane module was due to the existence of particulate matters, colloidal matters and organic matters in feeding water and their deposition on the membrane surface. The deposition rate of fouling materials increased with the increase of the average treated water (permeation) rate (permeating water load per unit membrane area) and the module recycle rate (which affected the concentration polarization). Therefore, the overly high system average permeation rate and the system recycle rate can easily lead to a higher fouling rate and more frequent chemical cleaning. Design guidelines were empirical values obtained by a comprehensive study based on the design and operation data of a large number of engineering projects involving different types of water sources, and the system was designed according to these guidelines so as to reduce the cleaning frequency in operation and prolong its life cycle.

In the posttreatment and system cleaning steps, a reasonable RO system was designed for different feeding
water sources and permeating water quality in the hope of reducing the cleaning frequency, prolonging the cleaning cycle, improving the long-term stability of the system and reducing its operating cost.

Test conditions and operation procedures of the actual factory units

The data of the parameter test results of actual factory units shown in Figure 3 were recorded and analyzed in the hope of finding the optimal parameters suitable for this water source and smooth operation of RO membrane, which are as follows:

1. After the results indicated that the feeding water met the requirements by testing and analyzing the feeding water of the device, the adjustment of feeding water could be conducted only;
2. The pressure control of water supply pump and automatic water quality monitoring system were adjusted;
3. It should carry out the inspection to see if all pipelines of the device were perfectly connected, if the pressure gauges were complete, if the joints of low-pressure pipelines were tight and sufficient;

4. The discharge valve in front of the pump was turned on, the pretreatment equipment was started and the water supply rate was adjusted to make it greater than the feeding water rate of the device;

5. All pressure gauge switches, water inlet valves, concentrated water outlet valves and permeating water outlet valves were fully turned on.

6. The outlet valve in front of the pump was turned off, and the water feeding valve of the device was turned off after the module was fully filled with water;

7. When the inlet pressure of the high-pressure pump was greater than 0.2 MPa, the high-pressure pump was started, and the water feeding valve of the device was turned on slowly while the concentrated water discharge valve was turned off. The total pressure difference of the device was controlled to be less than 0.3 MPa; after the permeating water was discharged for 2 min, the permeating water outlet valve was turned off, the device was running for 15 min and all the high- and low-pressure pipelines and instruments should be inspected to see if they work normally.

8. The water feeding valve and concentrated water outlet valve were adjusted so that the ratio of permeating water to concentrated water was 3:1;

9. The conductivity of permeating water was inspected, and when it met requirements, the permeating water outlet valve was turned on first and then the permeating water outlet valve was turned off.

10. Notes on the adjusting process:
   (1) The water feeding pressure should not be greater than 1.5 MPa during adjustment.
   (2) If the feeding water temperature was higher or lower than 25°C, it should be corrected according to the water temperature-permeating water flow rate curve, and the recycle rate should be controlled to be 75–90%.
   (3) After the device runs continuously for 4 h, if the desalination rate could not reach the designed removal rate, the desalination rate of each component of the device should be inspected, and faulty components (if any) should be replaced.
   (4) When it was found that there was water leakage in the high-pressure pipeline, the pressure of the device should be relieved, and it was strictly forbidden to loosen the high-pressure joint under high-pressure condition.

The test of and comparison between traditional pure water RO membrane CPA3-LD and anti-fouling recycle membrane LFC3-LD are shown in Table 3.

**RESULTS AND DISCUSSION**

In this study, the process of polarizing plate factory was run by using the RO membrane system equipment for more than 3 months, where KI waste liquid was concentrated by anti-fouling RO membrane while RO permeating water was recycled so that it enters the water purification system for transportation.
Figure 3 | Study and test equipment drawing and photos of actual factory test units.
reuse. The system stability was proven by raw water quality analysis, RO membrane selection, RO membrane microanalysis and system test in an actual factory; the recycle effect of chemical cleaning was analyzed and the optimization of parameters was made according to the data change. Finally, the economic benefits of the recycle period of actual factory were evaluated.

### Analysis on the quality of raw water

It can be observed from Day 1 to Day 5 that the TOC value is between 0.58 and 0.79, which is less than 1 ppm and better than the TOC requirement of 3 ppm for tap water quality. During the 3 months of operation, the water quality meets the standard of recycling TOC of less than 1 ppm. The conductivity value of water sample is 2,899–3,298 μS/cm, and the pH value of wastewater is between 7.5 and 7.9. It can be inferred that this portion of water originates from ultra-pure cleaning without adding any chemical agents. Somewhat different from the pH of 7.5–7.9 of wastewater selected for this experiment, the water quality of this experiment was far superior to that of CMP, because too much oxidants and acid and alkali-containing substances were added to CMP water. Roche tube water was not recovered as the water quality of wastewater source was extremely complex. Too many variables would increase the treatment cost, thus reducing the treatment recycle rate and benefits.

### Recycle tests of waste liquid and water by using traditional RO membrane and anti-fouling RO membrane

#### Selection of RO membrane

RO membrane test results are plotted as shown in Figure 4. The test time was about 4 months. The pressure difference rising rate can be observed from the figure, which is far higher in the first stage than in the second stage. Therefore, the key factor is in the first stage. The conventional RO pressure difference at the beginning of the first stage was 1.5 kg/cm² and that of the LD anti-fouling membrane was 0.5 kg/cm². After continuous operation for 1.5 months, the blocking pressure difference was 5.6 and 2.9 kg/cm², respectively, and chemical CIP cleaning was carried out at the time to restore the pressure difference to 4.1 and 0.9 kg/cm². After continuous operation for 3 months, the blocking pressure difference was 7.6 and 7.1 kg/cm², respectively, and chemical CIP cleaning was carried out to restore the pressure difference to 6.0 and 0.9 kg/cm², respectively. Therefore, it could be clearly seen that the anti-fouling membrane could prevent blockage and had a cleaning restoration that was much better than that of the traditional membrane, so LFC3-LD membrane was chosen for actual factory testing.

### Microscopic analysis of RO membrane

There are four main causes of membrane fouling: adsorption and growth of microorganisms, adsorption of organic

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### Table 3 | Comparison of RO specifications for different applications

| Parameter                  | CPA3-LD                   | LFC3-LD                   |
|----------------------------|---------------------------|---------------------------|
| Membrane type              | NITTO CPA3-LD             | NITTO LFC3-LD             |
| Maximum feed flow (m³/h)   | 75 GPM (17.0 m³/h)        | 85 GPM (19.3 m³/h)        |
| Maximum operating pressure (bar) | 41.1                      | 41.1                      |
| Maximum operating temperature (°C) | 45                        | 45                        |
| Membrane active area       | 400 ft² (37.1 m²)         | 400 ft² (37.1 m²)         |
| Configuration              | Spiral wound              | Low fouling               |
| L (mm)                     | 1.016                     | 1.016                     |
| Weight (kg)                | 16.4                      | 12.5                      |
| Feed spacer                | 31                        | 34                        |
| Membrane surface charge    | (–) charge                | Neutral charge            |

### Table 4 | Analysis on the quality of raw water

| No. | Item   | Unit | Day 1    | Day 2    | Day 3    | Day 4    | Day 5    |
|-----|--------|------|----------|----------|----------|----------|----------|
| 1   | TOC    | ppm  | 0.67     | 0.79     | 0.58     | 0.66     | 0.61     |
| 2   | COND.  | μS/cm| 3,097    | 3,298    | 2,899    | 3,100    | 3,150    |
| 3   | KI     | ppm  | 405.8    | 393.4    | 385.2    | 423.5    | 414.5    |
| 4   | BO₂⁻   | ppm  | 180      | 220      | 198      | 260      | 123      |
| 5   | SDI    |      | 2        | 1        | 3        | 2        | 1        |
| 6   | pH     |      | 7.5      | 7.8      | 7.6      | 7.7      | 7.9      |
matters, aggregation of colloids and particulate matters, and precipitation of inorganic matters. In the process of practical application, the combined action of these four reasons leads to membrane fouling (Hsu et al. 2018). Zheng et al. (2018) found that analysis of the composition, formation mechanism and key factors of fouling in the process of RO wastewater regeneration in the study. Biological pollution and microbial community are considered as key contributors together in the results of SEM analysis. The fouling at the end cover and membrane entry also indicates significant biological fouling, and the vertical distribution of microbial community is found in the cross section of fouling. This study is helpful in clarifying the components and main contributors of RO membrane fouling and improving our understanding of membrane fouling mechanism and control strategy. In the comparison, Figure 6(a3), (a4)/(b3), (b4) shows the pure water and recycle spacer blockage and structural phenomena. As the water source of pure water membrane was tap water and the recovered water was potassium iodide wastewater, it was found that the spacer of recycle membrane was obviously polluted and blocked after operation, especially there was very obvious iodine deposit on the b4 grid, while it was clean on a4 grid. From the microscope observation in Figure 7, it can be seen that the pure water membranes a1–a8 are slightly polluted and blocked, while the recycle membranes b1–b8 have white crystals formed on the grid as shown in Figure 7(b8) (400×), which are pure potassium iodide crystals. In Figure 8(a)–8(h), there are not only white deposits on the net column but also gray-white granular deposits at the intersection of the net columns. It is speculated that it is because there were dead angles at the corners, and the deposition phenomenon is the most remarkable where the flow rate was the lowest.

In Figure 9(a)–9(d), when the crystals are observed at high magnifications of 700–3,500×, they are found to be potassium iodide crystals, and the width of the trace crystal substance is about 35–45 μm, which is gray-white at the highest point on the surface of the net column. On the surface of pure water RO membrane in Figure 10, the intercepted

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**Figure 4** | Comparison of pressure difference between conventional and LD technology RO membranes (membranes from NITTO).

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**Figure 5** | Comparison of cleaning pressure difference between traditional membrane and low-pressure RO membrane in 1st stage (membranes from NITTO).
particles observed in Figure 10(a) at 350× magnification are brown in color and analyzed as trace iron deposits in tap water, while obvious gray-black deposited particles observed in Figure 10(b) and 10(c) 700–1,400× are analyzed as SiO2 particles and trace iron deposits. On the surface of the recycling RO membrane, as shown in Figure 11(a)–11(d), the crystal substance on the surface, under the magnification of 350–2,450×, is found to be completely piled up at the highest place. Upon analysis, the gray iron deposits are mixed with the gray potassium iodide crystals.

In Figure 12(a)–12(d), translucent nematodes are surprisingly found in the surface substance in addition to colloidal dispersion at the magnification of 350–1,450×, with a quite large number and a length of about 180–200 μm. As the trace TOC in water is the food for nematodes to grow and absorb nutrients, it is also one of the main reasons for RO membrane bio-fouling. Yu et al. (2018) According to the study, different bacterial species and their extracellular polymeric substances (EPSs) significantly affected the fouling potential of RO membrane in the wastewater recycle, and EPSs components with molecular weight (MW) exceeding 10 kDa were separated by ultrafiltration membrane and proved to have higher membrane fouling potential.

Besides, through 3D micrographs in Figure 13(a)–13(c) (original color), Figure 13(d) and 13(e) (pseudo-color) and Figure 13(g)–13(l) (wire frame), it can be seen that the recovering RO membrane surface in brown is a stack of KI crystals, while Figure 13(j) and 13(k) shows that its height is about 0.907 μm (1.812 – 0.905 μm).

From Figure 14(a)–14(c), it can be further observed that the uneven accumulation of white potassium iodide crystal deposit on the grid support layer of the cross structure of KI_support anti-fouling membrane, the highest position of which is the red block in the upper left corner, with a height of 94.721 μm, and the stacking height of white potassium iodide crystal is 47.37 μm (green part). The red block at the highest position can reach a height of 94.721 μm.

Practical operation test of RO system in a factory

Relationship between the pressure loss and time of RO system

We can discuss the stability of RO membrane system from two aspects. The first one is to make a curve analysis of ΔP of the system, i.e., pressure difference vs time (Figure 15). First, observe Table 1, when ΔP was 3.3 kg/cm2 on the 14th day, chemical washing was conducted, in which NaOH at pH = 12 was first used at normal temperature and then HCl at pH = 2 was used at normal temperature. As a result, ΔP was returned to 1.6 kg/cm2. The operation continued till the 38th day in the second step, when ΔP was 4.7 kg/cm2 and chemical cleaning was conducted. After cleaning with NaOH at pH = 12 at 45 °C, and then with HCl at pH = 2...
Figure 7 | Comparison between pure water RO membrane and recycling RO membrane spacer under microscope.

Figure 8 | KI crystal sediments of feed spacer of recycling RO membrane under a microscope.
at normal temperature, $\Delta P$ was returned to below 0.4 kg/cm², indicating that NaOH heating was very effective.

Relationship between permeating water flow rate and time of RO system

Another factor to be discussed is the curve of time vs permeating water flow rate. If the curves are consistent with our design values, for example: this system is designed to produce permeating water flow rate of 10 m³/h within 3 months. If after the blockage, the water flow rate can be restored to 10 m³/h after chemical cleaning, the system should be stable at this time. Otherwise, chemical cleaning should be done as just described to achieve recuperability. In Table 1 and Figure 16, after 14 days of operation, the initial flow rate was decreased from 16 to 8 m³/h. As described above, it was restored to 13.5 m³/h after chemical cleaning. And when the operation continued till the 38th day, the permeating water flow rate was once again reduced to 8 m³/h, but was restored to the initial of 16 m³/h after chemical cleaning with NaOH at pH = 12 at 45 °C, indicating that heating
has an obvious relation to the restoration of water flow rate.

Combined comparison of pressure loss, permeating water flow rate with time

From the combined comparison of pressure loss vs permeating water flow rate vs time of RO system in Figure 17, it can be observed that the pressure loss, permeating water flow rate and time are negatively correlated. On the 14th day, when the pressure loss was increased to $\Delta P = 3.3 \text{ kg/cm}^2$, the permeating water flow rate was decreased to 8 m$^3$/h, and on the 38th day, when $\Delta P$ was increased to 4.7 kg/cm$^2$, the permeating water flow rate was decreased to 8 m$^3$/h. The RO system pressure loss value will decrease with the number of days, and the RO system water flow value will increase with the number of days, using time as the benchmark. It is obvious that the pressure loss is in reverse relation to the permeating water flow rate.
Another (approach) was the comparison between the feeding water KI concentrations of 390–466 ppm with the concentrated water KI concentration of 2,999–3,366 ppm. If KI concentration had no deviation but kept stable around 9–10 times the design value in 3 months, it would mean that the recycle membrane operated normally without damage.

Figure 13 | Crystal substance on the surface of recycled RO membrane under a 3D microscope.
Practical operation experience of RO system in a factory

1. In the polarization process, a large amount of water is used, and the discharge of wastewater generated from etching and pickling is continuous. In order to recycle the process water, RO membrane system is often used for wastewater recycling. There are several main control points in the RO system operation, which mainly depend on the liquid level of RO permeating water tank. The RO system permeating water recycle will be started when the liquid level is low, or when the feeding water tank of RO system is at an ultra-high level.

![Figure 14](https://doi.org/10.2166/wrd.2021.110)

(a–c) Crystal sediment on the surface of KI support anti-fouling membrane under a 3D microscope. Please refer to the online version of this paper to see this figure in color.

![Figure 15](https://doi.org/10.2166/wrd.2021.110)

Pressure loss vs permeating water flow rate

![Figure 16](https://doi.org/10.2166/wrd.2021.110)

Relationship between RO permeating water flow rate and time
2. To judge whether the RO membrane system operates normally and whether the equipment is damaged or not, we can observe the concentration of KI (potassium iodide) after the RO membrane system is used for 3 months. If the KI concentration is 9 to 10 times the design value, and the KI concentration of feeding water and that of concentrated water are always stable without deviation, both the RO membrane system and equipment are normal.

**Benefit evaluation**

The benefits are estimated for the recycle of cutting and grinding wastewater of an actual IC packaging and testing factory, which recovers 250 CMD wastewater at an operation water flow rate of 10.5 m³/h and a recycle rate of 85%. The consumables, electricity charges, labor cost, interest costs, etc. for the 5 years of operation, and the economic benefits of saving costs in the average annual recycle are estimated. The relevant consumables data for benefit evaluation are shown in Table 5.

If the owner directly discharges the wastewater without a recycle system, the costs for wastewater treatment and water pollution will be about US$ 168,630, and the cost for KI recycle will be about US$ 3,650,000. If the recycle system is used, US$ 3,709,579 can be saved per year, and the device will be recovered after about 0.08 year, as shown in Table 6.

In this study, the KI waste liquid from the polarizing plate factory is concentrated with anti-fouling RO membrane, and the permeating water of RO system is recycled so that it enters the water purification system for reuse, thus not only achieving the benefits of double recycles but also realizing the circular economy advocated by the government due to the increasing shortage of water resources. The recycle cost of RO water is about US$ 0.83/t, eliminating the water pollution fee and wastewater treatment fee of about US$ 1/t to be collected by the Bureau of Science and Technology. Assuming that the polarizing plate factory recycles 250 CMD wastewater per year, it can save annually US$ 3,709,579.

| Table 5 | Benefit Evaluation |
| --- | --- |
| Item | Name | Quantity | Unit | Unit price (USD) | Total price (USD) |
| 1 | RO membrane tube replacement (once every 2 years) | 15 | Unit/year | 833 | 125,00 |
| 2 | Cleaning chemical (NaOH 45%; once a month) | 60 | kg/year | 0.2 | 12 |
| 3 | Cleaning chemical (Na-EDTA; once a month) | 60 | kg/year | 1 | 80 |
| 4 | 100 μm bag filter (change once a month) | 12 | Unit/year | 3 | 40 |
| 5 | 1-year labor cost for maintenance | 1 | USD/year | 16,667 | 16,667 |
| Total average annual maintenance cost |  |  |  | 29,298 |
| 5 years |  |  |  | 146,490 |
168,630 and is shown in Table 7. If the 2 CMD KI solution is recovered per day, about US$ 5/L, is added, the annual saving will be US$ 3,650,000 after deducting the operating cost of US$ 109,000.

Figure 19 shows the annual expenses to be paid by the company before and after the construction of water recycle system. Before the construction, the KI recycle fee, wastewater treatment fee, water pollution fee and water purification fee should be paid a total of US$ 3,818,630, but after the construction, only the operation fee and labor cost totaling US$ 109,015 should be paid. That is, the expense of about US$ 3,709,579 can be saved each year. According to this study, the recycle of the cutting and grinding wastewater from an actual IC packaging and testing factory can achieve the benefits of double recycles, which can not only achieve the purpose of water recycle but also realize the double benefits of circular economy advocated by the government. In the future, it is hoped that it can be popularized in all packaging and testing factories, which will not only bring business opportunities to manufacturers, save considerable expenses, but also reduce the pollution of the earth, save a lot of water resources and water treatment energy. It can really serve multiple purposes, and it is a recycling technology worthy of vigorous promotion.

Table 6 | Equipment recycle life

| Parameter                                      | Value  |
|-----------------------------------------------|--------|
| Recycled water volume                         | 10.5 m³/h |
| Total annual water yield of recycle           | 91,980 T/year |
| Electricity consumption per hour              | 32.0 kW |
| Electricity charge                            | 13,362 dollar US$/year |
| The annual recurrent expenditure (for equipment maintenance and electricity costs) | 109,015 dollar US$/year |
| Saving of the internal KI recycle volume of the factory | 750,000 L/year |
| Saving of the internal KI recycle fee of the factory (A) | 3,650,000 dollar US$/year |
| Saving of the internal wastewater treatment fee of the factory | 45,990 dollar US$/year |
| Saving of the wastewater pollution charges of the industrial area | 45,990 dollar US$/year |
| Saving of the DI water treatment fee of DI system | 76,650 dollar US$/year |
| Annual water saving (B)                       | 168,630 dollar US$/year |
| Savings of total years (A) + (B) = (C)         | 3,818,630 dollar US$/year |
| Annual cost savings (C)                       | 3,709,579 dollar US$/year |
| Initial equipment investment                   | 300,000 dollar US$ |
| Annual 1.5% interest rate of equipment investment | 4,500 dollar US$/year |
| Equipment recycle life                         | 0.08 year |

Table 7 | Economic benefit

| Economic benefit                              | Value  |
|-----------------------------------------------|--------|
| Saving of the internal wastewater treatment fee of the factory (1) | 45,990 dollar US$/year |
| Saving of the wastewater pollution charges of the industrial area (2) | 45,990 dollar US$/year |
| Saving of the DI water treatment fee of DI system (3) | 76,650 dollar US$/year |
| Savings of total years (1) + (2) + (3)         | 168,630 dollar US$/year |
II. The stability of RO membrane system can be discussed

I. There are two mechanisms that affect the permeating water flow rate of RO system: one is the blockage caused by the ion crystallization, and the other is the blockage caused by the biomembrane. KI (potassium iodide) chemical is generally added in the process to improve the recycle rate, but it can make the down tank (reaction tank) reach the peak period of reaction. When KI chemical is cleaned, the conductivity will become high, and when the RO conductivity removal rate is poor, it will make the recycled water quality unable to meet requirements and also indirectly affects the improvement of recycled water volume. Therefore, if RO membrane system runs stably, the good recycle efficiency can be achieved, the recycle system can produce permeating water stably, the concentration of KI will be relatively stable, and the recovered water quality can be purer.

II. The stability of RO membrane system can be discussed from two aspects. The first step is to analyze the curve of the pressure difference of the system vs time. The second step is that when the $\Delta P$ reaches 4.7 kg/cm$^2$ on the 38th day and cleaning with NaOH and HCl is conducted, if the $\Delta P$ returns to below 0.4 kg/cm$^2$, it indicates that the RO membrane system is very stable.

III. With the increase of time, the relationship between pressure loss and the RO permeating water flow rate will become negatively correlated. On the 14th day, when the pressure loss was increased to $\Delta P$ 3.3 kg/cm$^2$, the permeating water flow rate was decreased to 8 m$^3$/h, and on the 38th day, when $\Delta P$ was increased to 4.7 kg/cm$^2$, the permeating water flow rate was decreased to 8 m$^3$/h. It is obvious that the pressure loss is in reverse relation to the permeating water flow rate.

IV. To achieve the vision of effective utilization of water resources and meet the requirements of the management strategies and regulations for effective utilization of industrial water issued by relevant government departments, the economic benefits of water recycle are important, which depend on proper pipeline division, water flow diversion and economic scale of water recycle. About US$ 670,000 is needed for wastewater treatment and water pollution fees, while US$ 560,000 can be saved per year from the benefits of the recycle technology according to this study, for which the investment can be recovered in about 1.14 years.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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