End of Life Management of Electronic Waste

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INTRODUCTION

In the last decades, electronic devices have brought a revolution in every aspect of life, very often a fully operating device is discarded to follow the very rapid advancement of the technology. This generates a huge amount of electronic waste with a huge potential for recycling (Figure 1).

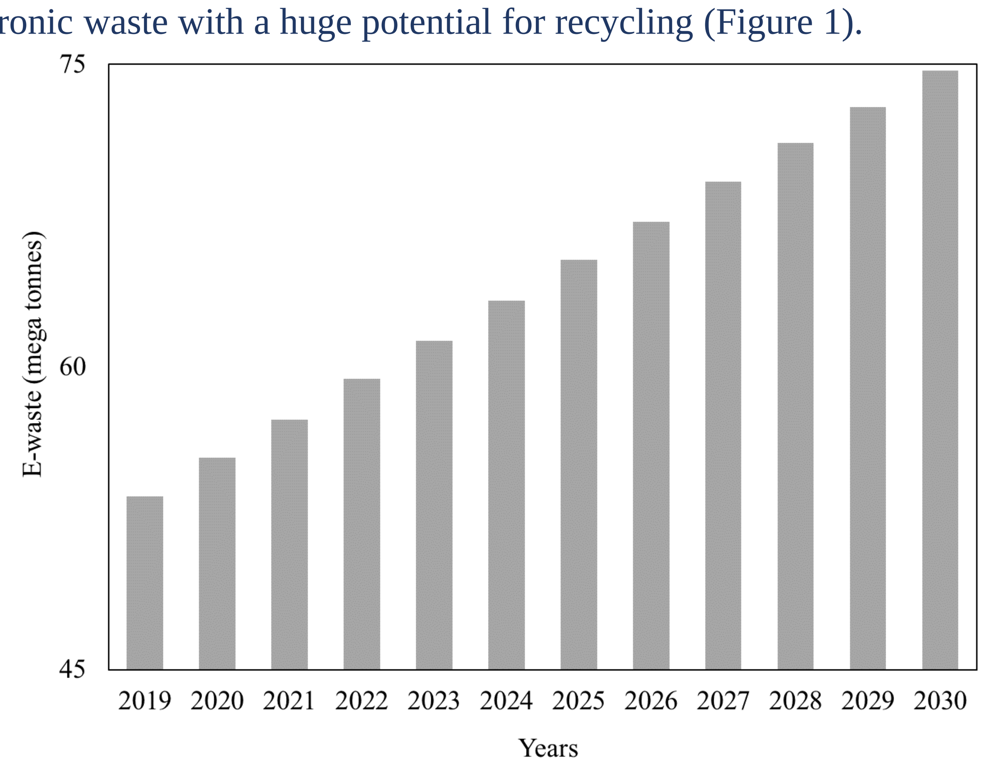

Figure 1: E-waste generation per year ([1,2])

However, on other hand End-of-Life (EOL) management of electronic products is not effectively approached due to the complexity.

OBJECTIVES

The implementation of suitable digital technologies into the recycling processes can make EOL management more efficient [3]. As shown in the Figure 2, simulations of the processes, can be helpful to identify the process parameters according to the different compositions and advanced visual techniques, such as Hyperspectral Imaging (HSI), can be useful for the identification of the material composition and, thus, provides information for further processes in EOL management [4-6]. Therefore, the first objective of this work is focused on developing a simulation of the particle trajectories in the separation process to identify the effective parameters for efficient separation, the second objective is the use of the HSI analysis technique to perform a material identification.

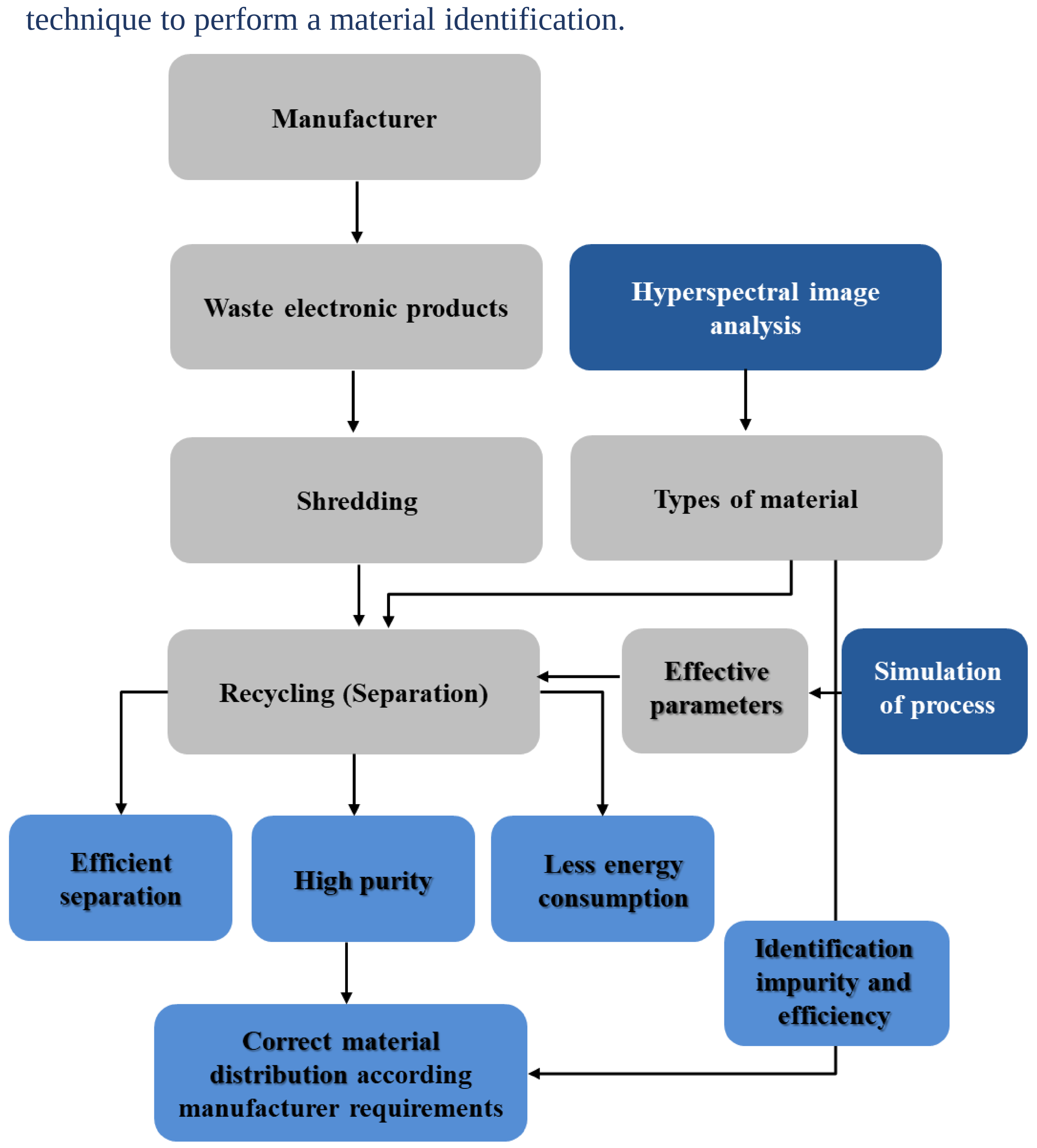

Figure 2: Recycling with simulation of separation process and hyperspectral imaging (HSI)

MATERIALS & METHODS

The corona electrostatic separator has been used to separate conductive and non-conductive particles by simulating the trajectory of the particles (Figure 3). Minimum voltage has been identified by using the critical length ($d_{nc} < d < d_c$), where d, d_{nc}, and d_c are distance at which one of the splitters is positioned from the roller, distance of the non-conductive and conductive particles at height h, respectively (Figure 4).

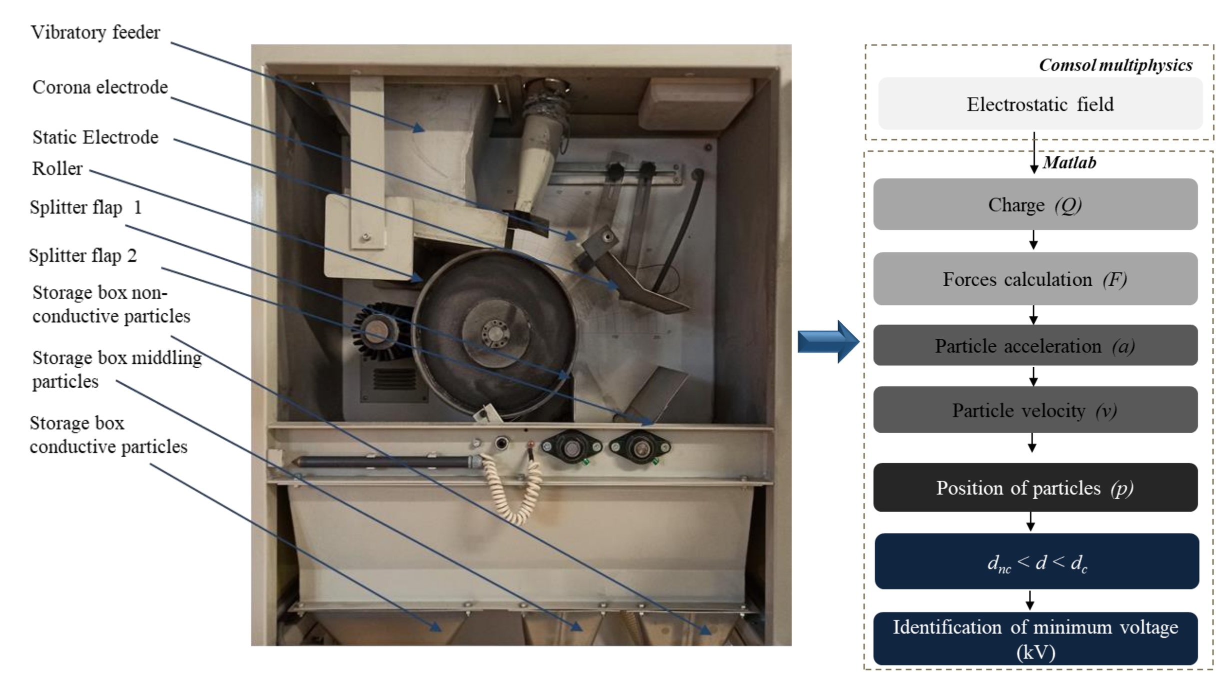

Figure 3: Corona electrostatic separator

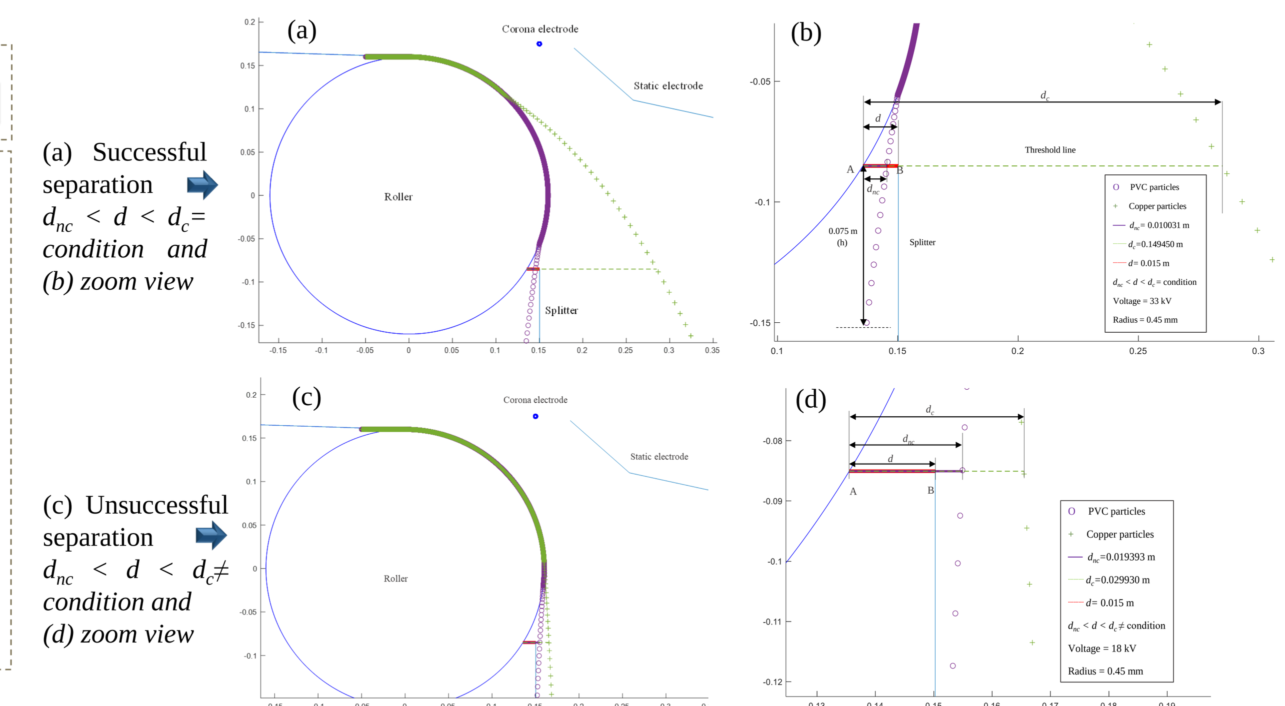

Figure 4: Particle trajectory simulation

As shown in Figure 5, a visible near-infrared (VNIR-HSI) push broom camera has been used for material identification combined with image analysis (Figure 6).

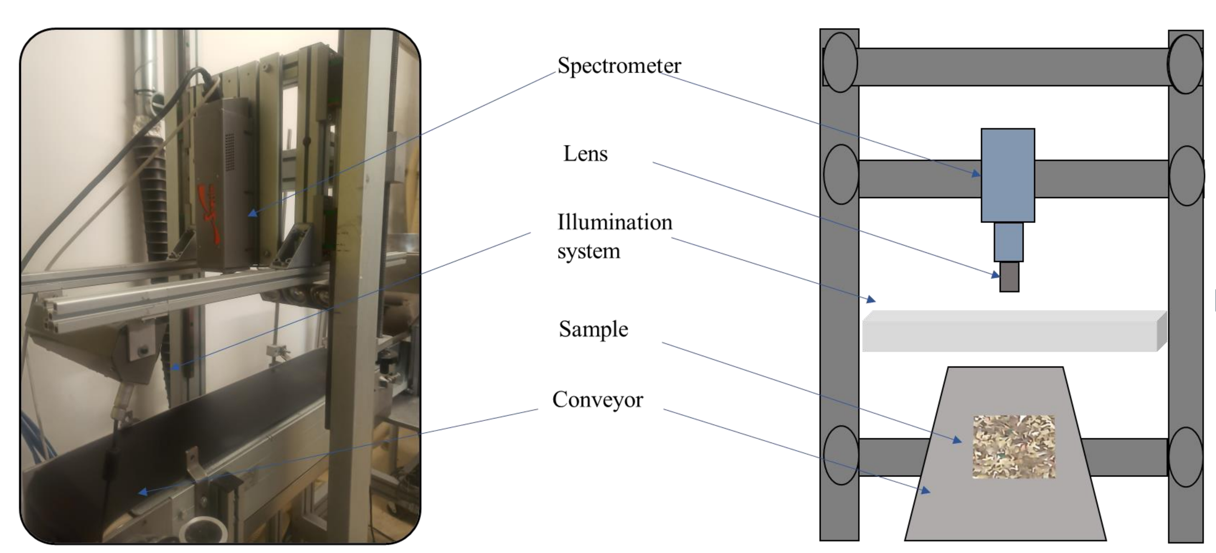

Figure 5: Hyperspectral imaging system

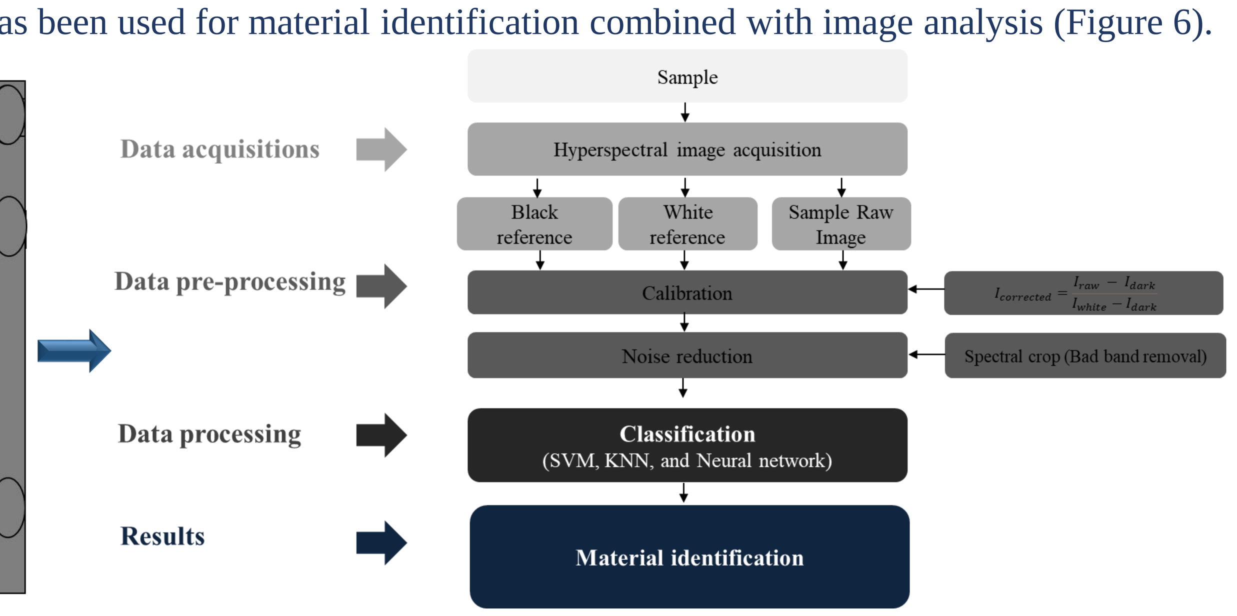

Figure 6: Image analysis for material identification

RESULTS

In this study, experimental campaign has been concducted by using electric cables, which are made of copper and PVC (0.4 to 0.5 mm). The bigger the particles, the higher the required voltage to separation, thus trajectories of copper and PVC particles 0.5 mm particle is calculated by using the condition mentioned above (Figure 7). The experimental trials are conducted from 27 kV, 26 kV and 25 kV and the efficiency of the separation for every trial identified at 33 kV as shown in the (Figure 8). Similarly, the HSI images of each fraction are captured at 27 kV, 26 kV and 25 kV trials (Figure 9). The 99% separation efficiency for both the fractions occurs at 26 kV, which is equal to the minimum voltage for 0.5 cylindrical shape particle.

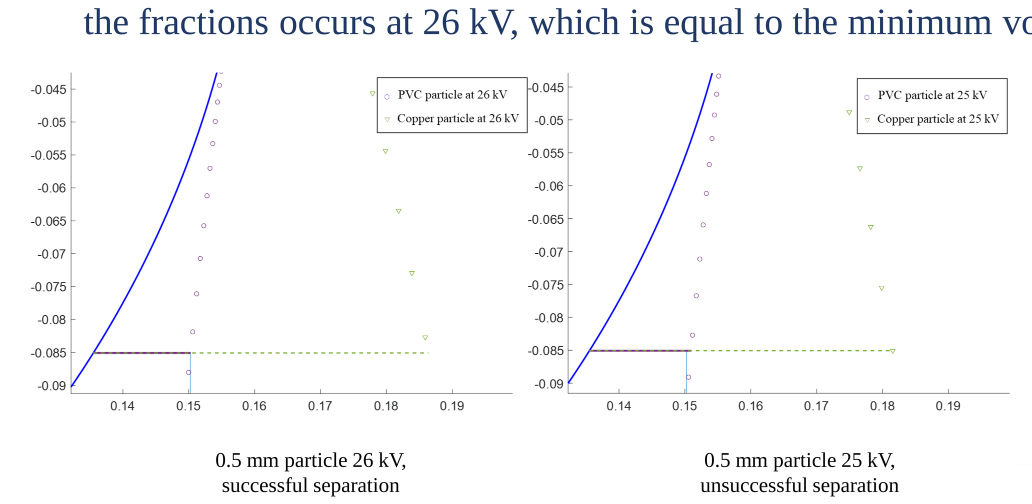

Figure 7: Particle trajectory (cylindrical particles)

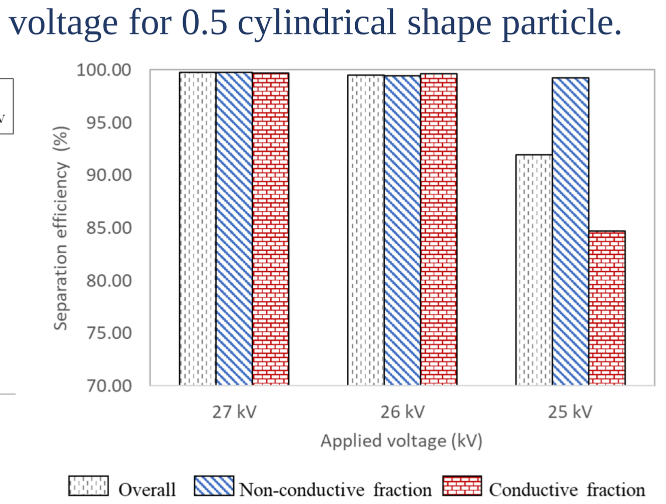

Figure 8: Separation efficiency of the 0.4 to 0.5 mm particles (experimental result)

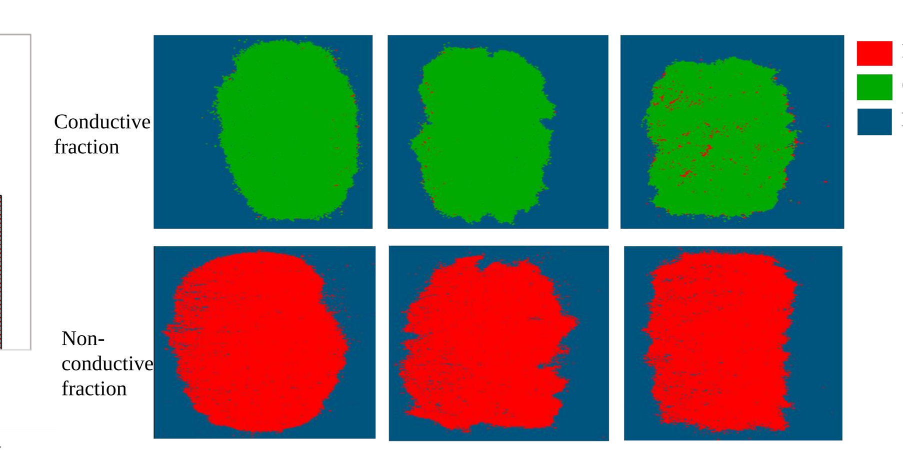

Figure 9: Analysed hyperspectral images

The specimen with three materials, commonly found in printed circuit boards, i.e. copper, ferrous and epoxy are analysed using HSI (Figure 10). The background class has the highest accuracy compared to the all other classes, which is always above the 99.8 %. The copper has shown lowest accuracy of 93.6% in the KNN model. The ferrous and epoxy has shown good accuracy in neural network and SVM, respectively compared to the KNN model results (Figure 11).

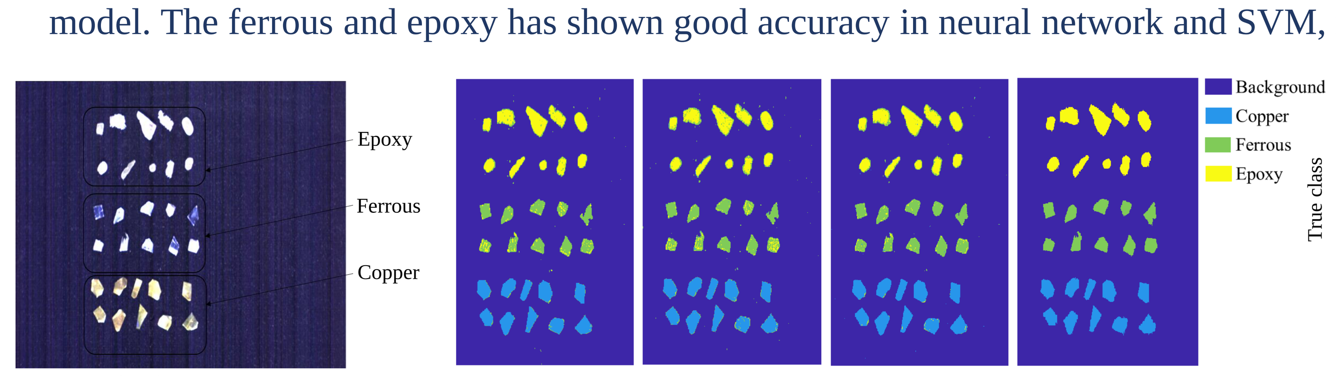

Figure 10: Specimen and prediction result

SVM

True class	B	Cu	Fe	Ep	TPR	FNR
B	99.9	0.0	0.1	0.0	99.9	0.1
Cu	1.8	94.5	3.5	0.2	94.5	5.5
Fe	3.5	0.0	85.9	10.6	85.9	14.1
Ep	2.8	0.1	18.8	78.3	78.3	21.7

KNN

True class	B	Cu	Fe	Ep	TPR	FNR
B	99.8	0.0	0.1	0.0	99.8	0.2
Cu	1.5	93.6	4.5	0.4	93.6	6.4
Fe	3.0	1.0	82.8	13.2	82.8	17.2
Ep	2.3	1.5	24.5	71.6	71.6	28.4

Neural network

True class	B	Cu	Fe	Ep	TPR	FNR
B	99.8	0.1	0.1	0.0	99.8	0.2
Cu	2.6	95.5	1.3	0.6	95.5	4.5
Fe	2.6	0.6	91.2	5.6	91.2	8.8
Ep	2.3	0.8	20.2	76.7	76.7	23.3

Predicted class

Figure 11: Confusion matrix (B: background, Cu: copper, Fe: ferrous and Ep: epoxy)

CONCLUSIONS

The current work aimed to investigate the potential of simulation and hyperspectral image analysis to improve the EOL management of electronic waste and eliminate the existing issues. A deeper knowledge of the separation process parameters helps to optimise the separation process, reduce the energy consumption and to improve the quality of the final products, providing economic and environmental benefits. In this context, simulation of the particle trajectory has enabled a very useful representation of the particle behaviour in the corona electrostatic separation process and it is very helpful to identify the most effective parameters to increase the separation efficiency. In this work, simulation of the particle trajectory of the corona electrostatic separator is validated by identifying the minimum voltage required for a successful separation. Similarly, knowing the minimum voltage by using the simulation model can decrease energy consumption in corona electrostatic separators, leading to economic advantages like lower electricity usage, operating expenses and indirect greenhouse gas emissions.

Similarly, this study has demonstrated the use of VNIR-HSI to identify materials in electronic waste. Moreover, this work has covered pre-processing methods such as reflectance calibration and bad band removal to eliminate noise. In particular, this study has pointed encouraging results in the characterization of three key materials such as copper, ferrous and epoxy in combination with machine learning models, such as SVM, KNN, and neural networks models. In real-world scenarios, this research illustrates the HSI as a technology with a vast potential for efficient recycling of electronic waste. Moreover, the use of vision systems based on hyperspectral imaging cameras integrated into recycling plants could improve the flexibility and robustness of current industrial recycling processes with significant benefits such as the recovery of material in a cost-efficient way, enhance the recycling rates and reduce landfill waste, consequently fostering the circular economy concept.

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