# BIOINFORMATICS FISH MORPHOLOGY DETECTION SYSTEM DEEP LEARNING METHOD USING MICROCONTROLLER-BASED CONVOLUTIONAL NEURAL NETWORK ALGORITHM

**Suhadi Suhadi [1]*, Sofyan Mufti Prasetiyo[2], Harnum Annisa Prafitia[3], and Andy Achmad Hendharsetiawan[4]**

[1] Department of Informatics Engineering, Faculty of Information Technology and Digital, Universitas Bani Saleh, Bekasi, Indonesia
[1] Ministry of Marine Affairs and Fisheries Republic of Indonesia, Jakarta, Indonesia
[2,3]National Research and Innovation Agency Indonesia, Jakarta, Indonesia
[2] Department of Informatics Engineering, Faculty of Informatics Engineering, Universitas Pamulang, Banten, Indonesia
[4] Department of Informatics Engineering, Faculty of Informatics Engineering, Universitas Bhayangkara Jakarta Raya, Jakarta, Indonesia
(E-mail: hadims71ndl@gmail.com)

## ABSTRACT
Fish are members of poikilothermic vertebrates that live in water and breathe with gills, fish are the most diverse group of vertebrates with more than 27,000 species worldwide, until now fish are generally consumed fresh. Fish can be processed into various products such as dried fish, fish jerky, shredded fish, fish crackers, salted fish, fish balls and fish blood flour as plant fertilizer and fish feed. Indonesia is the world's largest exporter of fisheries at 937,201.14 tons and national fish consumption is 54.9 kg/capita (2021). Artificial Intelligence (AI) is a technique used to mimic the intelligence possessed by living and non-living things to solve a problem. Deep Learning is a technique used in the development of neural networks that uses certain techniques to accelerate the learning process. Previous research used image processing-based to detect fish diseases. Bioinformatics is the study/application of computational techniques to manage and analyze biological information, including the application of mathematical, statistical, and informatics methods to solve biological problems and facilitate the identification and classification of fish species as part of biological methods for learning. The purpose of this research is to create a bioinformatics system for fish species detection using deep learning method with multi sensors (eyes, smell, color, texture, gills) based on microcontroller control system (arduino) and smartphone. The purpose of this research is to analyze and make a prototype tool to detect the type of skin color and fish eyes based on fish biology (bioinformatics) with deep learning method using microcontroller-based Convolutional Neural Network algorithm. The sample test verification result is a sampling error of 25% for FCL and 20% for FCE, so it can still be used as a tool for identifying fish species.

**Key words: Bioinformatic, Deep Learning, Microcontroller, Convolutional Neural Network**

## INTRODUCTION

The utilization of Information and Communication Technology (ICT) in the field of public services, especially in public service information, is a priority need and becomes a continuous service and provides the widest possible information, not just for prestige or lifestyle, but in its implementation, many obstacles are encountered by the public who do not have access to correct, relevant and up-to-date information, so that people are confused about the information provided from various decision makers, especially stakeholders who handle data and information. Strengthening the governance, accountability and public image of institutions will lead to improved institutional performance and the quality of products produced. This policy will be meaningful when associated with efforts to fulfill information services thoroughly, quickly, accurately and (1).

The computational capabilities of computers, many applications and algorithms that were previously impossible to implement on a laptop or laptop/netbook can now be implemented easily with a smartphone, one technique that has become popular is artificial intelligence (AI), becoming famous because many applications of this type can now be found everyday such as Siri on iPhone and speech recognition on Android cell phones. Along with the emergence of the term AI as the basis for the development of artificial intelligence, one of them is Deep Learning (DL) as a technique in the development of neural networks that use certain techniques to accelerate the learning process Bioinformatics (bioinformatics) is the study/application of computational techniques to manage and analyze biological information, including the application of mathematical methods, statistics, and informatics to solve biological problems and facilitate the identification and classification of fish species as part of biological methods for learning (2).

The development of smartphones and the internet is getting very fast so that use is also facilitated (smart), for the community the use of smartphones and the internet raises a new knowledge for the community itself in utilizing technological developments, especially the use of smartphones and the internet to explore information. Housewives as the driving force for nutritional fulfillment in the family provide cooking solutions every day, the process will be carried out repeatedly to meet the nutritional needs of the family in terms of food served. The choice of side dishes as part of the food every day must be present and makes one of the prerequisites for eating, one of the products is fish which will be consumed freshly, for example fish is fried, grilled, cooked in other ways or even eaten raw statumi. With inaccurate and not up-to-date information, the average housewife buying fish in the market cannot distinguish fish worthy and unfit for consumption because there is no accurate information as a reference, this is dangerous for people's health if the fish turns out to be unhealthy. By utilizing smartphone technology with a fish type detection application, the information obtained will be easier and more accurate because with this technology smartphone users simply take a photo of the fish to be purchased, with the process of bioinforatics technology and deep learning can conclude that the fish is feasible and not feasible to consume (3).

The development of smartphones and the internet is getting very fast so that use is also facilitated (smart), for the community the use of smartphones and the internet raises a new knowledge for the community itself in utilizing technological developments, especially the use of smartphones and the internet to explore information. Housewives as the driving

force for nutritional fulfillment in the family provide cooking solutions every day, the process will be carried out repeatedly to meet the nutritional needs of the family in terms of food served. The choice of side dishes as part of the food every day must be present and makes one of the prerequisites for eating, one of the products is fish which will be consumed freshly, for example fish is fried, grilled, cooked in other ways or even eaten raw statumi. With inaccurate and not up-to-date information, the average housewife buying fish in the market cannot distinguish fish worthy and unfit for consumption because there is no accurate information as a reference, this is dangerous for people's health if the fish turns out to be unhealthy. By utilizing smartphone technology with a fish type detection application, the information obtained will be easier and more accurate because with this technology smartphone users simply take a photo of the fish to be purchased, with the process of bioinforatics technology and deep learning can conclude that the fish is feasible and not feasible to consume (4). The purpose of this research is the analysis and manufacture of prototype tools to detect the type of skin color and fish eyes based on fish biology (bioinformatics) with deep learning methods using the microcontroller-based Convolutional Neural Network algorithm.

## METHODS

### Proposed Methodology

Before conducting the research, a standard methodology was used as shown in Figure 1. starting from problem definition, approach, application development, to public implementation, accuracy measurement and conclusion.

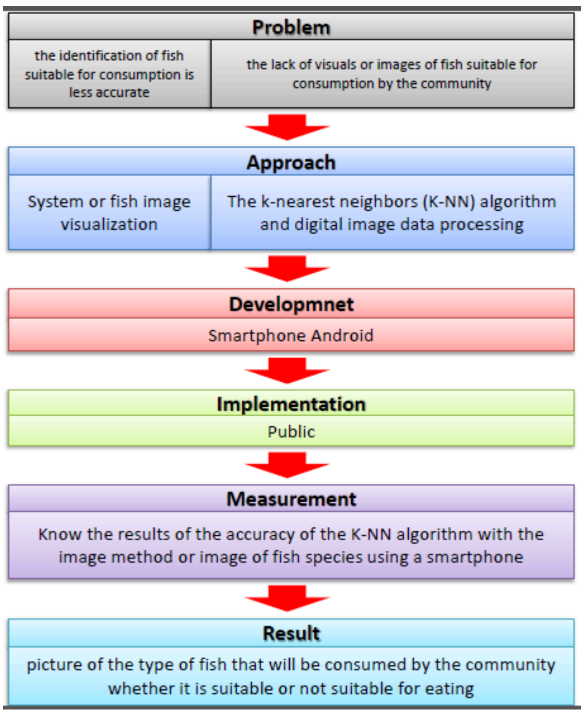


**Figure 1.** Proposed methodology

### Fish

Fish are members of poikilothermic vertebrates that live in water and breathe with gills, fish are a diverse group of vertebrates with more than 27,000 species worldwide, until now fish are generally consumed fresh and sold online. Fish can be processed into various products such as dried fish, fish jerky, shredded fish, fish crackers, salted fish, fish balls and fish blood meal as plant fertilizer and fish feed. Indonesia is the world's largest exporter of fisheries at 937,201.14 tons and national fish consumption is 54.9 kg / capita, the Indonesian people's consumption needs for fish are quite high reaching around 13 million tons of fish / year, while capture fisheries production is 7.5-8 million tons / year while for aquaculture is 6.5 million tons / year (5). The general shape of the fish species as shown in Figure 1.

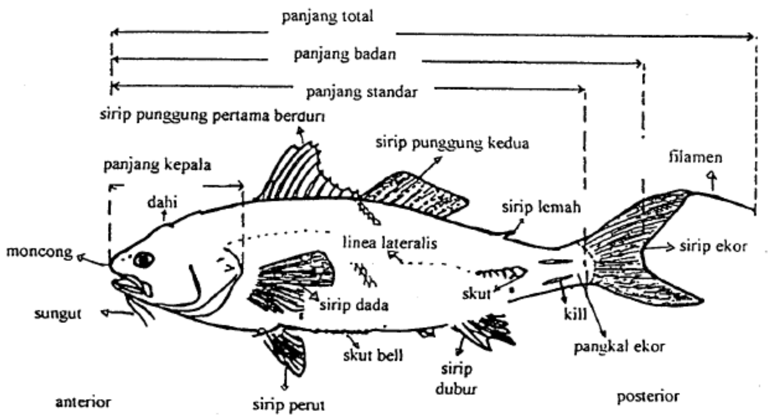


**Figure 2.** Morphology of fish species in general

**Fish Leather Color**

The color of healthy fish skin looks bright and not dull and has intact and firm scales and a bright skin color indicates that the fish is of high quality. While the color of unhealthy fish has a skin color that looks dull and not shiny and the scales are easily detached, there is no mucus, and the appearance is dull. The color of a healthy fish is bright and not dull and has intact and firm scales and the bright skin color indicates that the fish is of high quality. While the color of unhealthy fish has a skin color that looks dull and not shiny and the scales are easily detached, there is no mucus, and the appearance is dull (6).

**Figure 3. Color of fish species**

**Fish Eyes**

The characteristics of fresh fish eyes have bright, clear and convex eyes, if seen by the naked eye can be seen clearly and shiny. Meanwhile, fish that are not fresh usually tend to have blurry eyes and look pale (7). Draw the eyelets as in Figure 4.

**Figure 4. Color of fish species**

**Deep Learning**

Deep Learning is a subset of artificial intelligence and machine learning which is the development of multiple layer neural networks to provide accuracy for tasks such as object detection, speech recognition, language translation and others. Deep Learning differs from traditional machine learning techniques, as deep learning automatically performs representations of data such as images, videos or text without introducing coded rules or human domain knowledge (8).

**Bioinformatics**

Bioinformatics is the study/application of computational techniques to manage and analyze biological information, including the application of mathematics, statistics, and informatics methods. Solving biological problems and facilitating identification and classification of fish species as part of biological methods for learning (9).

**Image Processing**

Image processing is a method for processing images (images) into digital form for certain purposes, which serves to improve and improve the quality of an image, but with the times and the emergence of computational sciences it allows humans to retrieve information in an image. The input is an image (picture) and the output is an image that has been improved in quality (10).

**Sensor**

Sensors are devices used to detect changes in physical quantities such as pressure, force, electrical quantities, light, movement, humidity, temperature, speed and other environmental phenomena. After observing the changes, the detected input will be converted into an output that can be understood by humans either through the sensor device itself or transmitted electronically through a network to be displayed or processed into useful information for its users, in general in the classification of sensors there are active sensors and passive sensors and digital and analog sensors (11).

**RGB System**

RGB (Red, Green, Blue) is an additive color model, where three light beams are added together, by adding wavelengths, to create the final color (12). The RGB function is used to analyze the coverage of warrants on skin and fish eyes with the following equation formula.

$$\overline{X} = \sum_{n=1}^{1} Xi \quad \ldots\ldots (1)$$

$$\overline{X}_y = \frac{\left[\frac{R_y + G_y + B_y}{3}\right]_2 + \left[\frac{R_y + G_y + B_y}{3}\right]_R}{2} \quad \ldots\ldots (2)$$

$$R_y = \left[\frac{(R_i + R_r)}{2}\right] \ldots\ldots (3)$$

$$G_y = \left[\frac{(G_i + G_r)}{2}\right] \ldots\ldots (4)$$

$$B_y = \left[\frac{(B_i + B_r)}{2}\right] \ldots\ldots (5)$$

Variable R, G, B are red value, green value, and blue value, respectively with the standard value as shown in Table 1.

Table 1. RGB Color Function

| Color | Nominal Range | White | Yellow | Oyan | Green | Magenta | Red | Blue | Black |
|---|---|---|---|---|---|---|---|---|---|
| R | 0 to 255 | 255 | 255 | 0 | 0 | 255 | 255 | 0 | 0 |
| G | 0 to 255 | 255 | 255 | 255 | 255 | 0 | 0 | 0 | 0 |
| B | 0 to 255 | 255 | 0 | 255 | 255 | 255 | 0 | 255 | 0 |

The RGB result values can be seen in Table 2 with membership functions for low and high ranges for skin and fish eye colors.

Table 2. RGB Color Function

| **Method** | **Input** | **Range** | |
|---|---|---|---|
| | | **Low** | **High** |
| $\overline{X}_{RGB}$ | Fish leather | 90-125 | 105-140 |
| $RGB_{EG}$ | Red fish leather | 75-120 | 97-135 |
| | Green fish leather | 75-112 | 147-190 |
| | Blue fish leather | 60-98 | 97-151 |
| $\overline{X}_{RGB}$ | Fish eye | 89-122 | 104-136 |
| $RGB_{EG}$ | Red eye | 71-115 | 94-132 |
| | Green eye | 73-110 | 145-182 |
| | Blue eye | 60-98 | 97-151 |

Digital image is a two-dimensional image that can be displayed on a computer screen as a set/discrete digital values called pixels/picture elements. In a mathematical view, image is a continuous function of light intensity in a two-dimensional plane (13). the formulas for finding a digital image are shown (7) – (10):

$$r = \frac{R}{R+G+B}, \; g = \frac{G}{R+G+B}, \; b = \frac{B}{R+G+B}$$
………………………. (6)

$$v = (r, g, b)$$ ……………………………………………. (7)

$$S = \{0, \quad if\ V = 0\ 1 - \frac{(r,g,b)}{v}, V > 0$$
………………………………. (8)

$$H = \{0, \quad if\ S = 0\ \frac{60*(g-b)}{S*V}, if\ V = r\ 60 * \left[2 + \frac{b-r}{S*V}\right], if\ V = g\ 60 * \ [4]$$
…………………………... (9)

$$H = H + 360\ if\ H < 0$$ ……………………………………
(10)

Where each element in a digital image (meaning matrix element) is called an image element, picture element or pixel or mop. Therefore, an NM-sized image has a pixel NM. For example, suppose a unit is 256x256 pixels and is represented numerically by a matrix consisting of 256 rows (indexed from 0 to 255) and 256 columns (indexed from 0 to 255).

## RESULT AND DISCUSSIONS

The analysis technique used is to use a test test model in the form of a flowchart which is used as the basis for finding suitable variables so that the process becomes valid, as in the flowchart image, as an Figure 5.

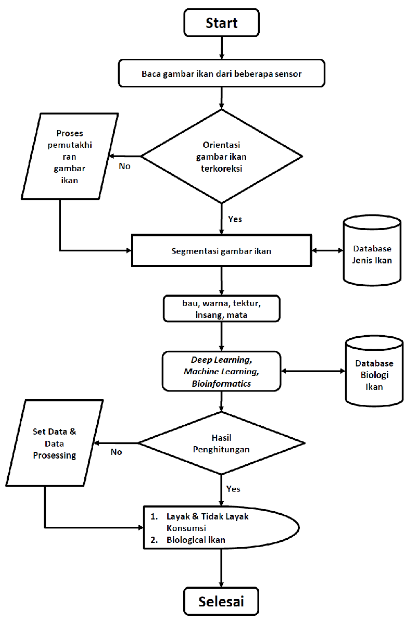


**Figure 5.** Object Image Validation Test Flowchart

The analysis technique used to test and analyze image processing algorithms with CNN algortima with test tests used as a basis for finding in processing suitable variables so that the process becomes valid, test case studies on fish include.

**Data Training**

The data used in this study is to use 20 test times for 4 days with objects for color and fish eyes. The sample test data will be used as training data for analysis as shown in Table 3.

Table 3. Training data of color and fish eye value test results

| Sample test to | Days | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Fish Color Leather (FCL) | | | | Fish Color Eyes (FCE) | | | |
| | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 |
| 1 | 0.63 | 0.82 | 0.52 | 0.40 | 0.24 | 0.72 | 0.14 | 0.49 |
| 2 | 0.76 | 0.15 | 0.30 | 0.40 | 0.24 | 0.05 | 0.14 | 0.49 |
| 3 | 0.30 | 0.40 | 0.30 | 0.10 | 0.29 | 0.30 | 0.19 | 0.49 |
| 4 | 0.74 | 0.10 | 0.52 | 0.00 | 0.03 | 0.10 | 0.10 | 0.09 |
| 5 | 0.80 | 0.15 | 0.30 | 0.65 | 0.40 | 0.05 | 0.30 | 0.74 |
| 6 | 0.69 | 0.55 | 0.50 | 0.85 | 0.06 | 0.45 | 0.90 | 0.94 |
| 7 | 0.80 | 0.65 | 0.15 | 0.01 | 0.04 | 0.55 | 0.40 | 0.02 |
| 8 | 0.80 | 0.40 | 0.78 | 0.83 | 0.59 | 0.30 | 0.49 | 0.92 |
| 9 | 0.30 | 0.40 | 0.30 | 0.90 | 0.90 | 0.30 | 0.80 | 0.99 |
| 10 | 0.17 | 0.40 | 0.30 | 0.65 | 0.03 | 0.30 | 0.20 | 0.74 |
| 11 | 0.80 | 0.60 | 0.55 | 0.15 | 0.40 | 0.50 | 0.30 | 0.24 |
| 12 | 0.30 | 0.60 | 0.55 | 0.65 | 0.04 | 0.50 | 0.60 | 0.74 |
| 13 | 0.30 | 0.40 | 0.80 | 0.40 | 0.40 | 0.30 | 0.30 | 0.49 |
| 14 | 0.05 | 0.40 | 0.30 | 0.56 | 0.52 | 0.30 | 0.42 | 0.65 |
| 15 | 0.05 | 0.65 | 0.55 | 0.83 | 0.40 | 0.55 | 0.30 | 0.92 |
| 16 | 0.05 | 0.65 | 0.80 | 0.40 | 0.62 | 0.55 | 0.52 | 0.49 |
| 17 | 0.05 | 0.24 | 0.30 | 0.40 | 0.23 | 0.14 | 0.13 | 0.49 |
| 18 | 0.30 | 0.15 | 0.69 | 0.40 | 0.15 | 0.05 | 0.05 | 0.49 |
| 19 | 0.30 | 0.65 | 0.30 | 0.15 | 0.90 | 0.55 | 0.80 | 0.24 |
| 20 | 0.11 | 0.40 | 0.19 | 0.40 | 0.40 | 0.30 | 0.30 | 0.49 |

**Test Data**

The calculation shows the distance value of R, G, B as zero, so the calculation can be known directly. This means that the outer and inner eye circles are equally close so the value is absolute. And to see the test results that have been carried out on the FCL test, FCL1-FCL20 and FCE1-FCE20 can be seen in Table 4.

Table 4. Sample test verification result

| Sample Number | Fish Color Leather (FCL) | | |
|---|---|---|---|
| | Verification Result | Result | Score |
| FCL01 | Fresh | Fresh | 1 |
| FCL02 | Fresh | Fresh | 1 |
| FCL03 | Fresh | Fresh | 1 |
| FCL04 | Not Fresh | Not Fresh | 0 |
| FCL05 | Fresh | Fresh | 1 |
| FCL06 | Fresh | Fresh | 1 |
| FCL07 | Fresh | Fresh | 1 |
| FCL08 | Not Fresh | Not Fresh | 0 |
| FCL09 | Fresh | Fresh | 1 |
| FCL10 | Fresh | Fresh | 1 |
| FCL11 | Not Fresh | Not Fresh | 0 |
| FCL12 | Fresh | Fresh | 0 |
| FCL13 | Fresh | Fresh | 1 |
| FCL15 | Not Fresh | Not Fresh | 1 |

| | | | |
|---|---|---|---|
| FCL16 | Fresh | Fresh | 0 |
| FCL17 | Fresh | Fresh | 1 |
| FCL18 | Fresh | Fresh | 1 |
| FCL19 | Fresh | Fresh | 1 |
| FCL20 | Not Fresh | Not Fresh | 0 |
| **Sample Number** | **Fish Color Eye (FCE)** | | |
| | **Verification Result** | **Result** | **Score** |
| FCE01 | Fresh | Fresh | 1 |
| FCE02 | Fresh | Fresh | 1 |
| FCE03 | Not Fresh | Not Fresh | 0 |
| FCE04 | Fresh | Fresh | 1 |
| FCE05 | Fresh | Fresh | 1 |
| FCE06 | Fresh | Fresh | 1 |
| FCE07 | Fresh | Fresh | 1 |
| FCE08 | Not Fresh | Not Fresh | 0 |
| FCE09 | Fresh | Fresh | 1 |
| FCE10 | Fresh | Fresh | 1 |
| FCE11 | Fresh | Fresh | 1 |
| FCE12 | Fresh | Fresh | 1 |
| FCE13 | Not Fresh | Not Fresh | 0 |
| FCE15 | Fresh | Fresh | 1 |
| FCE16 | Not Fresh | Not Fresh | 0 |
| FCE17 | Fresh | Fresh | 1 |
| FCE18 | Fresh | Fresh | 1 |
| FCE19 | Fresh | Fresh | 1 |
| FCE20 | Fresh | Fresh | 1 |
| FCE18 | Fresh | Fresh | 1 |
| FCE19 | Fresh | Fresh | 1 |
| FCE20 | Fresh | Fresh | 1 |
| FCE18 | Fresh | Fresh | 1 |
| FCE19 | Fresh | Fresh | 1 |
| FCE20 | Not Fresh | Not Fresh | 0 |

A CNN classifier was developed to distinguish between five classes. This classifier consists of twelve main layers, including six convolution layers layer 1-3 into three max pooling layers FCL1 - FCL3, FCE1 - FCE3 and CNN1-CNN3, max pooling layers X1, X2, and X3 following the convolution of FCL, FCE and CNN layers respectively. Layers from layer 1-3 will form the perceptual network for feature extraction of feature extraction. The layers contain filters and trainable features from the map, layers X1-X3 contain 64, 64, 128, 128, 256, and 256 trainable filters with 3 pixels each. The trainable filters have a relationship with the previous layer. The result is first summed with the trainable bias, to form a feature map, then put into the linear activation function of unsaturated unit (ReLU) and then into the batch normalization function, the result of CNN architecture analysis as shown in Figure 6.

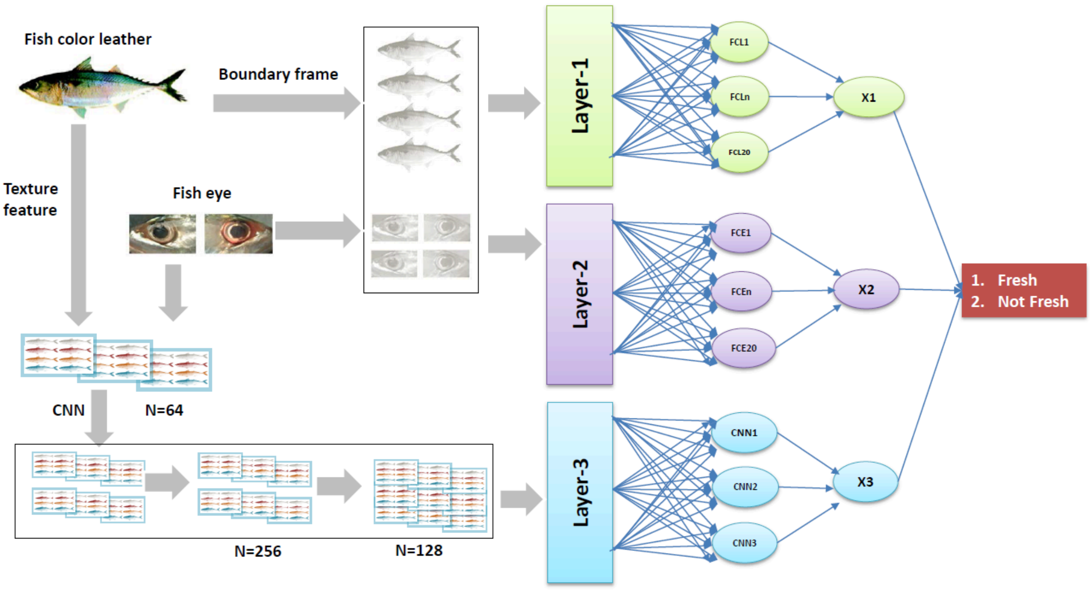


**Figure 6.** Architecture of the proposed CNN classifier

Separation of gill tissue from fish images using image processing algorithms based on segment clustering dat image processing, the most informative region of the image for freshness range discrimination. The experimental results show that the segmentation method for clustering is an efficient and accurate method for classification and the wavelet transform coefficients of the segmented ROI using provide discriminative coefficients for freshness as in Figure 7.

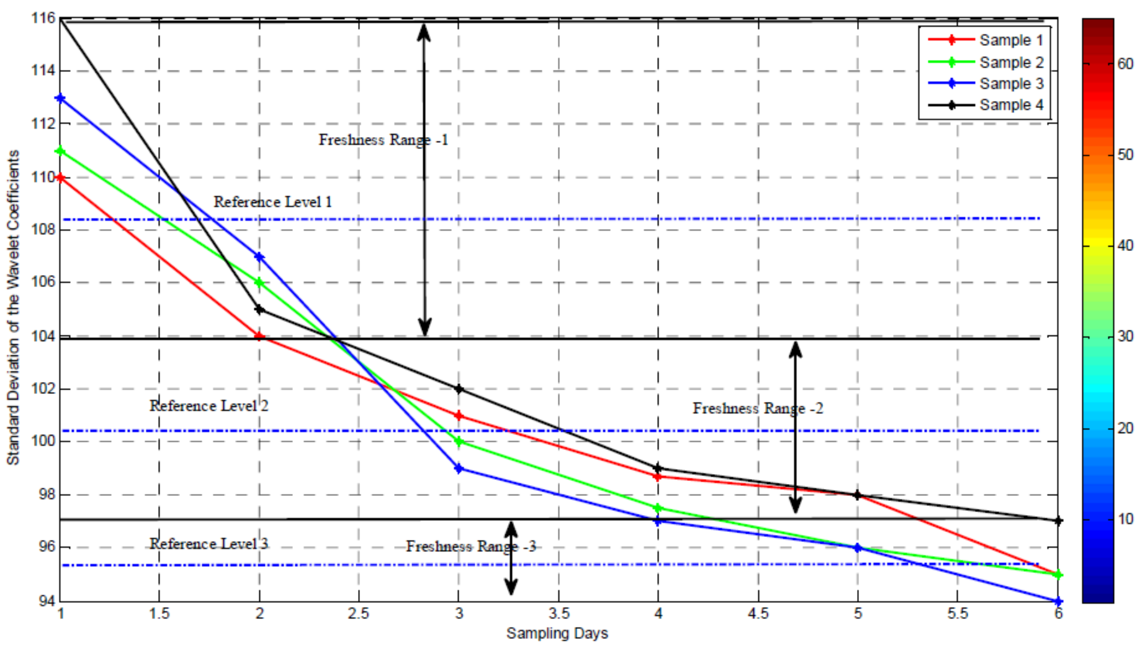


**Figure 7.** Variation of ROI wavelet features on fish samples

The wavelet transform coefficients of the segmented ROI using provide discriminative coefficients for the freshness ranges. The reference level specified for each range helps the algorithm to classify the input samples for the freshness range based on the distance from the reference level will be effective even though there are differences in the freshness ranges for the two static parameters, hence it can be considered as a robust and comprehensive method for classification of fish samples for freshness, as in Figure 8.

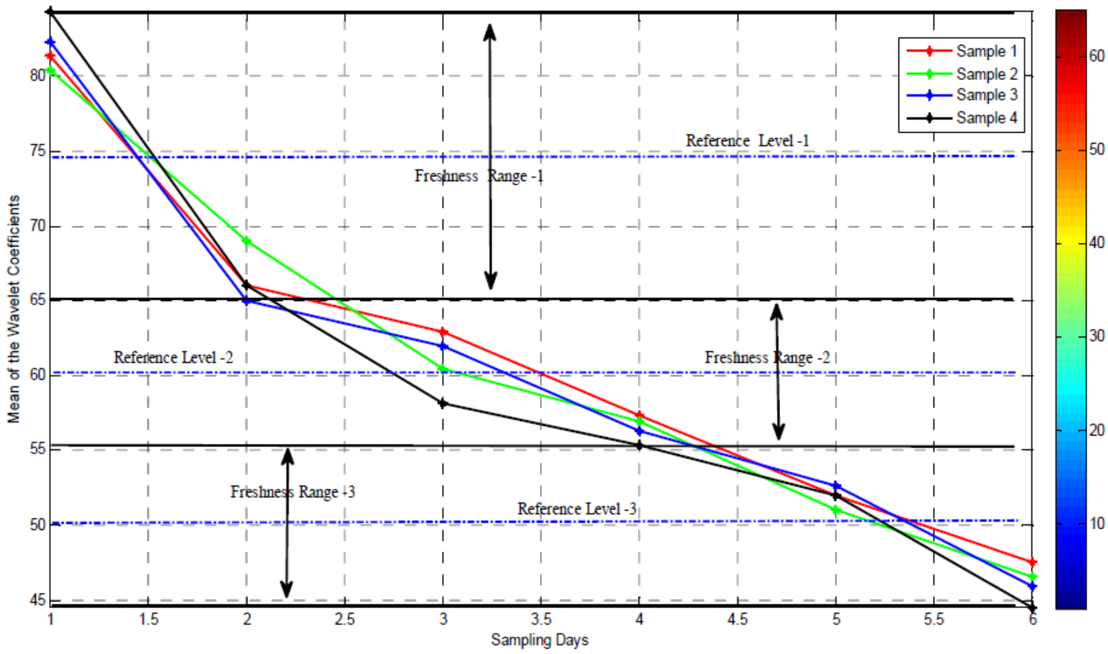


**Figure 8.** Average variation in ROI of fish samples

While the final results in this study for the overall process are made in the form of a prototype tool, the function of the tool is to be used as a bioinformatics analysis learning for fish species morphology detection systems and can be used to analyze the process of determining the condition of fish species based on the fish family using deep learning with microcontroller-based convolution neural network algoritm as shown in Figure 9.

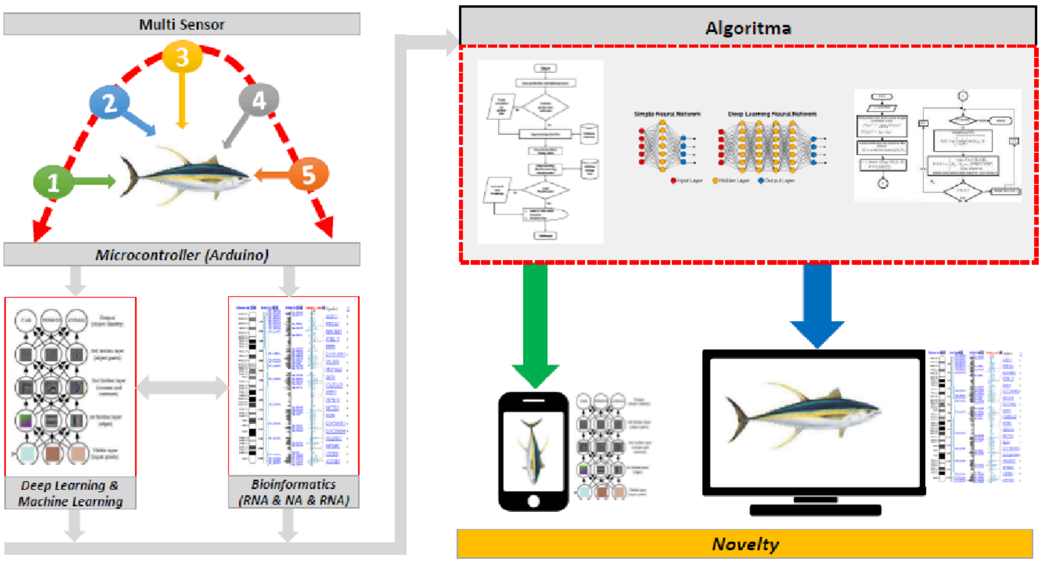


**Figure 9.** Fish Detection System Prototype Results

## CONCLUSION

Consumers will need guidance in checking the condition of products, especially fresh fish products, while researchers will use analysis for further research. Based on the results of this study, the analysis to perform the process using training data that has been prepared with image processing methods shows the ability to classify the type of fresh or not fresh fish based on image detection of fish skin and fish eyes. The results of the analysis on the sample test verification result is a sampling error of FCL of 25% and for FCE of 20%, so there are still external factors that cause the error is less lighting and the camera used in this study uses low pixels. This prototype can certainly be developed for other types of fish and other fresh products, such as vegetables and fruits, and using other more sophisticated methods such as computer vision.

## REFERENCES


1. Javaid M, Haleem A, Singh RP, Suman R. Enabling flexible manufacturing system (FMS) through the applications of industry 4.0 technologies. Internet Things Cyber-Physical Syst [Internet]. 2022;2(April):49–62. Available from: https://doi.org/10.1016/j.iotcps.2022.05.005
2. Diwan AD, Harke SN, Gopalkrishna, Panche AN. Aquaculture industry prospective from gut microbiome of fish and shellfish: An overview. J Anim Physiol Anim Nutr (Berl). 2022;106(2):441–69.
3. Lee YS, Park WH. Diagnosis of Depressive Disorder Model on Facial Expression Based on Fast R-CNN. Diagnostics. 2022;12(2).
4. Fayyadhila R, Junaidi A, Prasetyo NA. Implementasi Deep Learning Untuk Klasifikasi Citra Undertone Menggunakan Algoritma Convolutional Neural Network. J Dinda Data Sci Inf Technol Data Anal. 2021;1(2):52–62.
5. Asiva Noor Rachmayani. Kelautan dan Perikanan dalam angk tahun 2022. In: KKP. 2022. p. 6.
6. Albendea P, Tres A, Rafecas M, Vichi S, Sala R, Guardiola F. Effect of Feeding Acid Oils on European Seabass Fillet Lipid Composition, Oxidative Stability, Color, and Sensory Acceptance. Li E, editor. Aquac Nutr [Internet]. 2023 Jan 6;2023:1–19. Available from: https://www.hindawi.com/journals/anu/2023/6415693/
7. Teymouri Z, Shekarchizadeh H. A colorimetric indicator based on copper nanoparticles for volatile sulfur compounds to monitor fish spoilage in intelligent packaging. Food Packag Shelf Life [Internet]. 2022 Sep;33:100884. Available from: https://linkinghub.elsevier.com/retrieve/pii/S221428942200076X
8. Smith AG, Han E, Petersen J, Olsen NAF, Giese C, Athmann M, et al. RootPainter: deep learning segmentation of biological images with corrective annotation. New Phytol [Internet]. 2022 Oct 10;236(2):774–91. Available from: https://nph.onlinelibrary.wiley.com/doi/10.1111/nph.18387
9. Tywari B. Bioinformatics and Computational Biology. In: Singapore Pte Ltd: Springer Nature. 2022.
10. Vasudevan SK, Baskar A, Rajappa M, Murugesh TS. Digital Image Processing [Internet]. Boca Raton: Chapman and Hall/CRC; 2023. Available from: https://www.taylorfrancis.com/books/9781003217428
11. Chai Y, Liao F, editors. Near-sensor and In-sensor Computing [Internet]. Cham: Springer International Publishing; 2022. Available from: https://link.springer.com/10.1007/978-3-031-11506-6
12. Pena LF, Duro JR. Digital Image and Signal Processing for Measurement Systems. Digital Image and Signal Processing for Measurement Systems. 2022.
13. Gao W, Liao G, Ma S, Li G, Liang Y, Lin W. Unified Information Fusion Network for Multi-Modal RGB-D and RGB-T Salient Object Detection. IEEE Trans Circuits Syst Video Technol [Internet]. 2022 Apr;32(4):2091–106. Available from: https://ieeexplore.ieee.org/document/9439490/