

Review

Arduino-based devices in healthcare and environmental monitoring

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Abstract

Rapid increases in diseases and pandemics over the past years have led to the development of more affordable and accessible biosensing equipment, especially in underdeveloped regions. One of the open-source hardware that has the potential to develop advanced health equipment is the Arduino platform. This review emphasizes the importance of open-source technology, specifically the Atmel family of microcontrollers used in the Arduino development board, and the applications of the Arduino platform in biosensing technologies to advance PoC devices. Furthermore, the review highlights the use of machine learning algorithms to enhance the functionality of user-defined prototypes, aiming to realize PoC devices. It also addresses the successes and limitations of microcontrollers and machine learning in the development of PoC devices using open-source technology. The primary purpose of this paper is to investigate how the Arduino platform can be leveraged to create effective and affordable biosensing solutions, by examining the integration of Arduino with various types of biosensors. The review showcases the potential of Arduino to democratize and innovate biosensor technology. Lastly, this paper extends the investigation of applications of Arduino to general health care and environmental monitoring.

Abbreviations

AI	Artificial Intelligence
IOT	Internet of Things
PoC	Point of Care
RNA	Ribonucleic acid
Abs	Antibodies
Ags	Antigens
ELISA	Enzyme-linked immunosorbent assay
LoC	Lab-on-chip
POC	Proof-of-concept

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1 Introduction

The past decade has seen a rapid increase in the number of epidemics and pandemics, and this has prompted the development of cheaper and more easily accessible biosensing devices, particularly in under-resourced areas [1–6]. There is a range of modern means of addressing this issue of developing novel accessible biosensing devices which include integration of machine learning [7–12] integration of microfluidic devices [13] integration of 3D technologies, and the integration of quantum technologies [14–17]. Another way to develop these devices is to integrate open-source hardware and biosensing technologies. This work aims to review progress in the development of such technologies. The invention of the first thermostat in 1883 marked the beginning of modern sensors [18]. Since then, sensors have evolved from simple devices producing basic output signals to sophisticated systems enhanced by computing, pervasive communication, and cloud integration [18–21]. Technology has made it possible for patients and in-home care providers to use sensors in healthcare. That is; after being first proposed by Clarke and Lyons in 1962 and put on the market in 1975, biosensors have grown to be a multibillion-dollar industry [21]. They are used in home health tests, such as for pregnancy and allergies, and environmental monitoring to detect water contaminants. Richard Feynman's 1959 lecture on Micro-Electro-Mechanical Systems (MEMS) inspired advancements that led to commercial sensors in the early 1990s, enabling numerous health and wellness applications [22, 23]. Since then, MEMS technology has produced small, accurate, and affordable sensors for various devices, from sports watches to cars [22, 23]. On the other hand, recent advancements in information and communications technology (ICT) have integrated microcontrollers, wireless communication, and data storage into sensors, resulting in smart sensors capable of digital signal processing and wireless data streaming [24–26]. Wireless body area networks (WBANs), introduced around 1995, use multiple sensors to measure and transmit physiological data wirelessly. Some of the emerging trends include the widespread consumer adoption of sensors, increasing availability in commercial markets, and integration into sports and wellness products. The rise of personal environmental monitoring, crowdsourced data via smartphones, and continuous miniaturization of sensors will drive the future of the Internet of Things (IoT) [27–30]. Conversely, advanced data mining and machine learning will reveal patterns in sensor data, leading to personalized health insights and collective intelligence.

One of the open-source hardware that has the potential to develop future health technologies is the Arduino platform. Arduino is an open-source electronics platform based on easy-to-use hardware and software. It consists of a variety of boards that can read inputs—such as a light on a sensor, a finger on a button, or a Twitter message—and turn them into outputs, like activating a motor, turning on an LED, or publishing something online [31–33]. Arduino boards are designed to be simple and flexible for both beginners and advanced users, providing a wide range of capabilities for diverse applications in electronics and embedded systems. The Arduino project began in 2005 at the Interaction Design Institute Ivrea in Italy, created as an affordable and accessible way for students to work with microcontrollers [34]. Founders Massimo Banzi, David Cuartielles, Tom Igoe, Gianluca Martino, and David Mellis developed the first Arduino board as a tool for rapid prototyping [34]. Over the years, the platform has evolved to include a variety of boards and modules, each tailored to specific needs and complexities. The development of the Arduino platform has been driven by a strong global community, contributing to its software, hardware designs, and extensive documentation. Arduino boards (Fig. 1) typically feature a microcontroller, digital and analog input/output (I/O) pins, and serial communication interfaces, all of which can be programmed using the Arduino Software (IDE). Some of the key components of the platform include:

- Microcontroller: The brain of the board, usually from the Atmel family (e.g., ATmega328P).
- Digital I/O Pins: Used to read or write digital signals.
- Analog I/O Pins: Used to read analog signals from sensors.
- Power Supply: Options for USB or external power sources.
- Communication Interfaces: Serial, I2C, and SPI interfaces for communication with other devices.
- Shields: Expansion boards that add functionality such as Wi-Fi, GPS, and motor control.

The code on an Arduino can be implemented using Tinkercad (Fig. 2). Tinkercad is an online 3D modeling and simulation tool that includes a built-in Arduino simulator. This feature enables users to create, program, and test Arduino projects virtually before implementing them with physical hardware [36–39]. Furthermore, the Tinkercad allows activities such as designing circuits, Arduino programming, and project simulations. These activities can be performed as follows:

[a] Arduino Uno (R3)



[b] Arduino Due



[c] Arduino Mega



[d] Arduino Nano



[e] Arduino Esplora



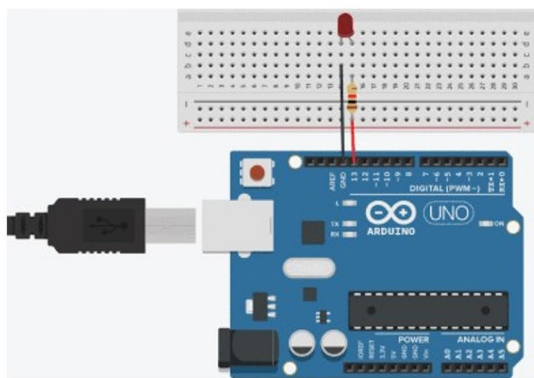
[f] Arduino Zero



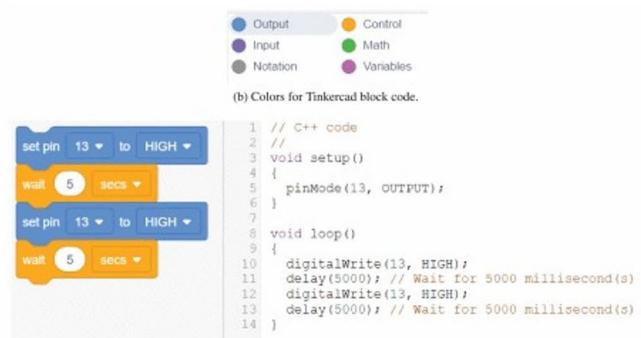
[g] Arduino Leonardo Board



Fig. 1 This image shows variants of the Arduino boards which include **a** Arduino Uno, **b** Arduino Due, **c** Arduino Mega **d** Arduino Nano. The Arduino Uno is an open-source microcontroller board that uses the ATmega328P microcontroller from Microchip. Arduino Due uses the Atmel SAM3X8E ARM Cortex-M3 CPU, and the microcontroller serves as the foundation for the original Arduino board. Arduino Mega is based on ATmega2560, which has then been upgraded to Arduino Mega2560. The Arduino Nano, also known as the Arduino Nano 3.x, is a compact, feature-rich, and breadboard-friendly board based on the ATmega328. Arduino Zero is a 32-bit expansion of the Arduino UNO, it offers improved performance to the board and broadens the family of Atmel microcontrollers. The Arduino Leonardo does not require a secondary processor, as the ATmega32u4 has a built-in USB connection. Lastly, the Arduino Esplora offers a variety of integrated, usable onboard sensors for interaction [35]



[a] Tinkercad Arduino example to turn on LED



[b] Code example in Tinkercad

Fig. 2 This image shows an example Tinkercad codebase on Arduino to light up an LED. Arduino projects and codes can be designed and simulated using Tinkercad, a free online program that eliminates the need for actual hardware [49]

- **Design Circuits:** Allows for the creation and simulation of electronic circuits using a variety of components, including Arduino boards, LEDs, sensors, and more.
- **Program Arduino:** Write and upload code to virtual Arduino boards using a built-in code editor that supports Arduino programming languages (C/C++). You can use the drag-and-drop code blocks or write text-based code.
- **Simulate Projects:** Run simulations to see how your code interacts with the designed circuit, allowing you to troubleshoot and refine your project before building it physically.

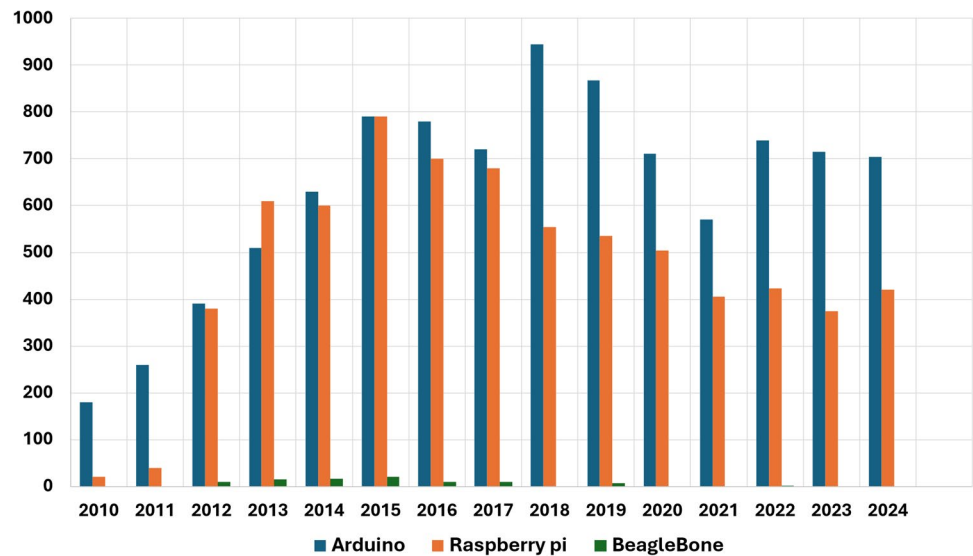
Tinkercad's Arduino simulation feature is particularly useful for beginners, educators, and hobbyists, as it provides a risk-free environment to learn and experiment with Arduino programming and electronics.

In recent years, the Arduino platform has revolutionized electronics and embedded systems by providing an accessible and versatile environment for hobbyists and professionals alike [40–42]. This paper reviews the application of Arduino in the field of biosensing, showcasing its potential to democratize and innovate biosensor technology. Biosensing is the process of detecting and measuring biological information using a biosensor, which is a device that combines a biological component with a physicochemical detector. Biosensors are crucial in various fields due to their ability to provide rapid, accurate, and specific detection of biological molecules, which is essential for diagnostics, monitoring, and research. Biosensors come in a variety of types e.g., Electrochemical biosensors which measure the electrical signals generated by the interaction between the target analyte and the biological element [13]. They are commonly used for glucose monitoring in diabetic patients. Another type of biosensor is an optical biosensor which uses light to detect biological interactions, measuring changes in light properties such as absorption, fluorescence, or refractive index. Some of the main biosensing applications include DNA sequencing, pathogen detection, and detection of temperature changes that result from biochemical reactions. The applications of the biosensors extend to medical diagnostics, environmental monitoring, and food safety [43–47]. Most importantly, they play a vital role in the early detection and monitoring of diseases, such as infectious diseases, cancer, and metabolic disorders [43, 44]. As a result, they have the potential for point-of-care (PoC) testing, to facilitate rapid and accurate diagnosis at the patient's bedside or in remote locations [43, 44]. Other extensive applications of biosensors include the detection of pollutants, toxins, and pathogens in the environment, ensuring the safety and quality of air, water, and soil [45, 46, 48]. They help in monitoring environmental changes and assessing the impact of human activities. In the food industry, biosensors are used to detect contaminants, pathogens, and allergens in food products. They ensure food safety and quality by providing rapid and reliable testing throughout the supply chain [45, 46].

New developments in open-source technologies are critical to modern laboratories. Up-to-date cutting-edge technology has demonstrated a reduction in the time required for the diagnosis and treatment of various diseases, particularly communicable diseases. The concept of timely diagnosis and treatment was realized in the early 1990s with lab-on-a-chip (LoC) technology, aimed at achieving chemical analysis of ultrasmall sample volumes, reducing both analytical time and reagent costs, and potentially increasing sensitivity [43–46]. Over the past three decades, researchers from diverse fields, including chemistry, biology, engineering, and physics, have worked to advance LoC technology into PoC applications. These efforts have led to the development of fully integrated devices capable of performing multiple tasks, such as sample preparation and analysis on-site, providing rapid results to medical professionals. Despite the emphasis on quick results, the PoC devices must be user-friendly, even for non-trained personnel, and cost-effective.

On the other hand, artificial intelligence, particularly machine learning-based predictive models, has the potential to enhance the performance of diagnostic devices to achieve the goals of LoC. Machine learning, a subset of artificial intelligence, is used in the medical field to predict diseases based on experience and data, offering advantages such as rapid classification, high accuracy, and sensitivity [50–55]. As infectious diseases remain a major cause of mortality, especially in developing countries; PoC diagnostics have the potential to alleviate this burden, necessitating the incorporation of easy-to-use and accessible technology. In this regard, this review emphasizes the importance of open-source technology, specifically the Atmel family of microcontrollers used in the Arduino development board, and the applications of the Arduino platform in biosensing technologies to advance PoC devices. A market study from 2010–2017 (Fig. 3) on integrating IoT and advanced technology design reported that Arduino is the most used open-source hardware platform in current embedded designs, with a usage rate of 5.6%. It is also the leading choice for future implementation, with 17% of respondents planning to use it. Raspberry Pi is the second most used platform, with a current usage rate of 4.2% and future consideration at 16%. BeagleBone comes third, with a current usage rate of 3.4% and a future consideration rate of 10% [56]. As such, this review further investigates alternative open-source platforms (Raspberry Pi, Beaglebone, Microsoft Sharks' Cave, and ESP32) to Arduino boards. Furthermore, the review highlights the use of machine learning algorithms to enhance the functionality of user-defined prototypes, aiming to realize PoC devices. It also addresses the

Fig. 3 This image shows the Google trends from 2010–2024 of the different open-source hardware technologies. The most popular open-source hardware platform for embedded designs is Arduino. Arduino is the most used open-source hardware platform in current embedded designs. The second-most-used platform is the Raspberry Pi. Third is BeagleBone [56]



successes and limitations of microcontrollers and machine learning in the development of PoC devices using open-source technology. The primary purpose of this paper is to investigate how the Arduino platform can be leveraged to create effective and affordable biosensing solutions; by examining the integration of Arduino with various types of biosensors, the current review aims to illustrate its potential to enhance the accessibility and functionality of biosensing applications across diverse fields.

This paper starts by providing a detailed introduction to the Atmel family of microcontrollers used in the Arduino development board. The next section discusses the open-source, software and hardware that is available for use or modification by users and developers. The discussion is extended to cover the Arduino microcontroller as an open-source platform and its advanced applications in healthcare and environmental monitoring using sensors and the incorporation of machine learning (ML) techniques. Lastly, the limitations and future of the microcontroller are discussed.

2 Open-source

Over the past years, Open-Source Software (OSS) has spread throughout many software industry sectors, making a computer community accept the software [57]. The OSS is a software that is licensed and distributed in a way that permits users to alter and share its source code [58]. One of the OSS licenses includes Free Software Foundation's General Public License (GPL); the license aims to prevent Free Software from becoming "taken proprietary" through its incorporation into programs whose source code is not made publicly available, while also ensuring that software users maintain the freedoms outlined in the Free Software documentation [57]. As such, GPL licenses are meant to promote a community in which those who gain from the efforts of others also contribute to their advancements. These have given rise to Open-Source Hardware (OSH), which includes fields such as open-source silicon, 3D printing, and electronics (best represented by the popularity of Arduino) [57, 59]. As such, open-source hardware licenses allow the people who receive the designs and documentation to examine them, make changes, and then share the changes. Furthermore, the project's documentation can be sold or given away without violating open hardware licensing.

3 Arduino platform as an open-source microcontroller

Microcontrollers are low-cost, programmable, compact integrated circuits designed to power an operation in an embodied system using various programming languages such as C++, Python, and C# [60–62]. The invention of microcontrollers can be traced back to the 1970s by Intel Corporation in the United States [63]. The design of these chips as initiated by Texas Instruments includes onboard memory with pins for input and output operations such as an interface for different sensors [63]. One of the popular microcontroller families is the Atmel family of microcontrollers used in the development of Arduino [64]. Arduino boards are relatively cheap, open-source, credit card-sized microcontroller boards. The

microcontrollers were invented primarily to enable less skilled people to design their prototypes [62, 65]. Today, Arduino is a standout platform because of the advantage it comes with [60]. It offers three main elements to provide a complete solution to prototyping, these elements are the Arduino board (the hardware part), the Arduino software, and the learning resources and documentation [60, 62]. This allows developers and everyone to easily create electronic prototypes for computer-controlled devices and standalone devices to perform operations of their choice. In both cases, Arduino boards can interpret and control many sensors and output devices on both software communication and network communication [60].

3.1 Arduino company

Arduino is a company focused on developing computer software and hardware that provides an open-source user project and community [62, 64]. The company designs and manufactures microcontroller-based kits to assist in developing digital devices that can sense and alter the physical world. The process of developing these digital devices is based on user-friendly programming, from which Arduino provides an integrated development environment (IDE) that supports programming languages such as C++, C, and Java [62]. As such the Arduino boards are compatible with embodied software prototyped in C++, C, and Java programming languages. Arduino projects are open-source; that is, all boards, electronic components specifications, and the IDE are available to end users at less cost [66, 67]. As such, the Arduino has received attention in research, as scientists have adopted the device for several applications [68–70]. Kaswan et al. [71] reviewed the roles of Arduino in real-world applications, one of the major reports is that the advantages such as standardized components, friendly programming, and lower prices are the driving force behind the realization of Arduino in research and development projects.

3.2 Arduino hardware

Arduino hardware is made up of a programmable microcontroller mounted on a circuit board to provide access to the microcontroller input/output pins and facilitate a connection to the personal computer for instruction sending/programming and the graphical user interface [62, 72, 73]. In addition, the physical configuration and the size of the circuit board allow interchanging of all Arduino-compatible boards [72]. On the other hand, the Arduino circuit boards allow for the plugging of standardized add-on boards to extend the capabilities of the main board called the shield [62, 72]. These add-on boards connect through mating pins positioned at the same physical configuration of Arduino board by plugging into the header on top of Arduino boards. Control of these add-on boards is facilitated by an Arduino microcontroller and a user-written program and is accessed from the Arduino pins [64].

3.3 Arduino software

The Arduino IDE provides a platform for end users to write their programs primarily by a C++ programming language, compile programs, and upload them to the microcontroller [74]. The IDE provides a terminal window to output text results from the Arduino board to the computer monitor. This software environment can be downloaded and installed for several operating systems, including Windows, Linux, and Mac OS X [64]. By using programming libraries in the IDE, end-users can integrate additional devices and sensors with no extensive programming [64].

3.4 Types of commonly used Arduino boards

There are several Arduino boards used for project development, some of the boards include the following:

- **Arduino Uno:** In Fig. 1a is an Arduino Uno, the board is powered by an Atmega328 processor that operates at 16 MHz [35, 75, 76]. It has 32 KB of program memory, 1 KB of Electrically Erasable Programmable Read-Only Memory (EEPROM), and 2 KB of random-access memory (RAM). This type of Arduino board is equipped with a pin header arrangement which makes it compatible with development board shields [35, 75, 76]. The microcontroller is 69 mm long and 54 mm wide with four screw holes.
- **Arduino Duo:** Arduino Duo is shown in Fig. 1b. It is powered by an ARM processor (AT915AM3X8E Cortex-M3) operating at 84 MHz on 3.3 V. The microcontroller has 512 KB of (read-only memory) ROM and 96 KB of RAM. Furthermore,

it has 54 digital I/O pins that consist of 12 analog inputs and 2 analog outputs, and 12 pulse width modulation (PWM) channels [35].

- **Arduino Mega:** Arduino Mega is shown in Fig. 1c. This type of Arduino is powered by an ATmega2560 with a clock speed of 16 MHz. The microcontroller consists of 256 KB of ROM, 8 KB of RAM, and 4 KB of EEPROM and operates at 5 V. It is also equipped with 54 I/O pins, 16 analog inputs, 15 PWM channels, and a deader pin [35, 77, 78].
- **Arduino Nano:** Fig. 1d is an Arduino nano; the latest version of the microcontroller is powered by an ATmega328 processor operating at 16 MHz. This type of microcontroller is equipped with 32 KB of program memory, 1 KB of EEPROM, 2 KB of RAM, 14 digital I/O, and 6 analog inputs with a power rail of both 5 V and 3.3 V [35, 79].
- **Arduino Esplora:** Arduino Esplora as shown in Fig. 1e offers a different board to the Arduino boards reported in this work. The board provides a built-in set of sensors. It is powered by ATmega32u4 operating at 16 MHz. It offers 32 KB of memory with 4 KB used for a bootloader, 2.5 KB of SRAM, and 1 KB of EEPROM, with an operating voltage of 5 V [35, 77, 78].
- **Arduino Zero:** The Arduino zero board is shown in Fig. 1f, the microcontroller is powered by Atmel's SAMD21 MCU processor operating at 48 MHz to provide an improved performance from the Arduino Uno. Furthermore, it provides 256 KB of flash memory, 32 KB SRAM, and 16 KB EEPROM. It offers 20 general-purpose I/O pins operating at 3.3 V [35, 77, 78].
- **Arduino Leonardo Board:** Leonardo board shown in Fig. 1g, is powered by ATmega32u4 processor with clock speed of 16 MHz. The microcontroller has 32 KB of flash memory with 4 KB reserved for the bootloader. Additionally, it has 2.5 KB of SRAM and 1 KB of EEPROM which is mainly read by EEPROM libraries. The board has 20 digital I/O pins operating at 5 V [35, 79].

3.5 Comparison of Arduino boards

In Table 1 are the specifications of the common Arduino boards. The physical dimensions of Arduino Nano are relatively smaller than those of all mentioned boards, followed by a medium-sized Arduino Uno. Arduino Mega and Arduino Duo are relatively larger boards sharing the same dimensions. In terms of processing power, the Arduino Zero leads with a big RAM/ROM [35]. Although the Arduino Mega is considered the larger Arduino with a large GPIO, it possesses the same CPU speed as the Arduino UNO, Nano, Esplora, and Leonardo. Therefore, it does not offer a speed advantage [35]. Both Arduino UNO and Nano use the same ATmega328 processor, making them identical in terms of hardware and peripherals [35, 79]. The Arduino Uno is embodied with a pin header, making it compatible with most development board shields. This increases the functionality while enhancing the capabilities of the Arduino board [35, 75, 76]. In terms of cost, Arduino Nano is the low-cost board in the market; hence they serve as a cost-effective for large projects. For the processing speed, the Arduino Duo operates at 84 MHz, a higher speed than other Arduino competitive boards [35].

3.6 Advantages of prototyping with Arduino

Arduino boards are relatively inexpensive platforms, with the most economical module costing less than \$50. Furthermore, the Arduino components can be bought and assembled with ease with DIY standards, as it takes a short time to fully prototype a system with Arduino. This is enabled mainly by the cross-platform capabilities of the boards [35, 80, 81]. That is, the IDE of the Arduino can operate on multiple operating systems such as Windows, Linux, and Macintosh OSX [82, 83]. This provides an easy-to-use programming environment with access to advanced tools to facilitate complex functions. Most importantly, the IDE and the software of the microcontroller are open source, allowing experts in programming to provide additional extensions and modifications to improve the performance of the platform. Due to this, the current Arduino programming language adopts extensively C++, allowing extension from the C++ libraries. It also mirrors the technical details of the language from the AVR C programming language. Hence, the platform can make use of the AVR-C code identically to the Arduino IDE code. Since the Arduino hardware is based on Atmel's ATMEGA8 and ATMEGA168 microcontrollers, it makes the Arduino hardware also open source with the modules published under a Creative Commons license [35, 80, 81]. This allows for new versions of the modules to be introduced by individual circuit designers, hence improving the module already on the market. As a result, the boards realize a rise in introductions to innovative technologies that can offer improved processing speed among others [35, 80, 81]. Currently, the Arduino boards in the market operate at the lowest voltage of 3.3 V to 5 V, making them more energy efficient. They also offer extendable pins to allow connection with external peripheral devices, such as universal resource locators (USB) to transfer resources. This further allows for a wide array of application program interfaces (API). In addition to the extendable pins,

Table 1 Arduino board specifications and prototyping

Board	Dimensions (mm)	CPU Processor	CPU Power	Voltage	Memory size	I/O pins	Prototyping
Arduino Uno	69 × 54	ATMega328	16 MHz	5 V	32 KB + 1 KB EEPROM + 2 KB RAM	14	Desktop prototyping, with Arduino shield
Arduino Due	101.52 × 53.3	AT91SAM3X8E	84 MHz	3.3 V	512 KB ROM + 96 KB RAM	54	High-performance prototyping with superior analog I/O
Arduino Mega	101.52 × 53.3	ATMega2560	16 MHz	5 V	256 KB ROM + 8 KB RAM + 4 KB EEPROM	54	High I/O requirements with more memory space
Arduino Nano	18 × 45	ATMega328	16 MHz	5 V	32 KB + 1 KB EEPROM + 2 KB RAM	14	Low cost, minor profile, simple projects
Arduino Esplora	164.04 × 60	ATmega32u4	16 MHz	5 V	32 KB of flash memory + 2.5 KB SRAM	–	Low cost scientific instruments
Arduino Zero	68 × 53	ATSAMD21G18	48 MHz	3.3 V	32 KB SRAM + 256 KB Flash memory + 16 KB EEPROM	20	Smart IoT devices, wearable technology, high-tech automation
Arduino Leonardo	68.6 × 53.3	ATmega32u4	16 MHz	5 V	32 KB flash memory + 2.5 KB of SRAM + 1 KB EEPROM	20	Smart GPS Tracker, Industrial Automation System

Arduino supports various sensors, which as a result make them ideal for prototyping systems that extend to imaging applications [35, 80, 81].

3.7 Limitations of prototyping with Arduino

Although the Arduino platform offers advantages, it comes with several challenges that result in limiting the applications of the modules. Arduino microcontrollers have a complex structure, making them capable of being manufactured in only a few parts of the world [84]. As a result, it limits the accessibility of the modules in the countries where they are not manufactured; with high demand in these countries, the cost of the modules also increases. Although the modules serve as easy to use compared to other types of microcontrollers, most people are not interested in making use of microcontrollers and there has been a lack of support from the government for the projects involving the development and propagation of Arduino preventing the Arduino to fully go mainstream [35, 80, 81]. This is due to that; the Arduino suffers from several drawbacks. The processing power of Arduino is weaker than the power of the microcontroller, as a result, Arduino is limited in terms of processing speed and power. Additionally, the modules have low memory that can allow storage only in the range of kilobytes (KB). Combining low processing power and low memory, the modules take longer to perform tasks that include scheduling and database storage. Therefore, Arduino cannot handle complex projects [35, 80, 81]. Individual evaluation of the Arduino boards, yields that, Arduino Uno is limited to only 14 digital I/O and 6 analog inputs, and it can operate at 5 V and 3.3 V [35, 75, 76]. On the other hand, the Arduino Duo operates only at 3.3 V; this type of microcontroller suffers from a reduced overvoltage which as a result leads to damage to the board [35]. Furthermore, the software compatibility with the Duo is always not certain. This is also realized in Arduino Mega, where the board is mostly compatible with Arduino shields but lacks software compatibility [35, 77, 78]. The Arduino Nano, on the other hand, cannot connect Arduino shields despite its equipment with pin headers [79]. In general, Arduinos are limited by their ability to run one task at a time. In the cases of using a microcontroller-based platform to control multiple sensors in developing a device, as well as ensuring stable and robust sampling of data and control of actuators, more computational power is required for processing and manipulation of sensor data, and the Arduino becomes insufficient [85].

3.8 Alternatives to Arduino boards

Figure 4b shows a representation of a Raspberry Pi. The Raspberry Pi is a series of small single-board computers (SBCs) developed mainly for the promotion of computer science in developing countries [86]. The microcontroller supports several operating systems including Windows 10 ARM 64, Windows 10 IoT core, Linux, FreeBSD, RISC OS, Plan 9, Net BSD, and Android [87]. As a result, the support for a wide range of operating systems has made the Raspberry Pi realize applications in advanced projects such as weather observations, robotics, and sensing [88–90]. The microcontroller is relatively affordable, costing approximately \$35. At this price, the compact board offers more processing power than the Arduino. The board extends its advantages by providing more interfaces for advanced connection; these include several GPIOs, Ethernet, onboard WIFI, and Bluetooth. It is relatively much easier to build applications with the Raspberry Pi since it supports popular programming languages such as Python and Linux with an available support community [91]. The Raspberry Pi boards run Linux on an SD card, as such the operating system (OS) of the boards runs on an SD card [92]. This poses a potential challenge to the board, considering the vibrations that the board may be exposed to, resulting in the termination of the functionality of the microcontroller. On the other hand, the microprocessor on the microcontroller produces heat that is usually poorly managed and affects the board's dependability [35]. As a result, the board has a limited life span, making projects developed with the microcontroller limited to a shorter life span [35]. During the lifetime operation of the boards, real-time events cannot be tracked, as the boards are not equipped with a real-time clock. Although Raspberry boards allow for the addition of RTC circuits to track real-time events, they come with an extra cost. Additionally, the boards do not have an onboard ADC, which forces designers to add an external ADC chip through a 12C/SPI for projects that may need ADC (8/10/12-bit resolution); this also adds more cost to the project. The Raspberry Pi is again not equipped with an EEPROM/FRAM/SPI for data storage of logging applications. The board has one universal asynchronous receiver transmitter (UART) on a header; hence, it does not allow eight signals creating a shortage of UART [35, 80, 81]. The Raspberry Pi uses a USB micro connector-based power supply, which cannot handle reverse voltage, surge, and overload, resulting in compromised projects. On the other hand, the board has 28 GPIOs on the header, resulting in limited I/O pins [35, 80, 81].

Another type of microcontroller that is commonly used as an alternative to Arduino boards is the BeagleBone, shown in Fig. 4a. BeagleBone is an open-source single-board computer with a low power consumption, developed for the sole

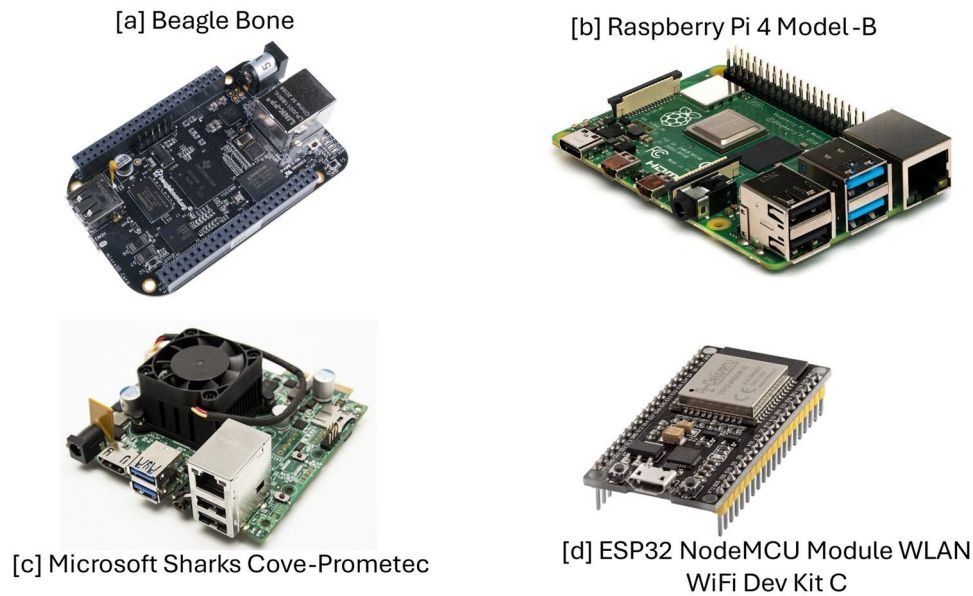


Fig. 4 Alternative microcontroller boards to Arduino **a** Beagle Bone, **b** Raspberry Pi 4 Model-B, **c** Microsoft Sharks Cove-Prometec, and **d** ESP32 NodeMCU Module WLAN WiFi Dev Kit C. A BeagleBone is an inexpensive, highly expandable, and developer-supported platform, it serves as a starting point for experimenting and learning to create hardware and software to program the processor and access the peripherals. The Raspberry Pi is a low-cost Linux computer with a set of GPIO pins that allows experimentation with the IoT and control of electronic components for physical computing. The Sharks Cove prototyping board is designed particularly for automation in robotics; it incorporates sensors, motors, LEDs, screens, and many more components. The ESP32 family of low-cost, low-power system-on-chip microcontrollers has dual-mode Bluetooth and Wi-Fi built-in [95, 98]

purpose of teaching open-source hardware and software capabilities [93]. The version of a BeagleBoard has more GPIO pins than the Raspberry Pi and is suitable for developing embedded systems and IoT projects [94]. The board is compatible with Ubuntu and Android 4.0, powered by an AM335 × 720 MHz ARM processor. It is also economically effective and provides an environment for ultra-low-latency sensor data and audio processing. However, the BeagleBone shares the same weakness as the Raspberry Pi [35]. Another microcontroller that is used as an alternative to Arduino boards, specifically for hardware development, is the Sharks Cove, shown in Fig. 4c. The Sharks Cove is a development board mainly used for hardware development and drivers for Windows OS [35]. The boards support driver development for various devices of interfaces such as GPIO, I2C, SDIO, and USB. The specifications of these microcontrollers are compared to that of the Arduino in Table 2. Lastly, the ESP32 as shown in Fig. 4d is also used to a large extent as an alternative to the Arduino board. They are potent System on Chip (SoC) microcontrollers that come with several peripherals, dual-mode Bluetooth version 4.2, and built-in Wi-Fi 802.11 [95]. ESP32 is a sophisticated successor to the 8266 chips, mainly in terms of implementing two cores with varying clock speeds up to 240 MHz. In addition to these improvements over its predecessor, it has 4 MB of flash memory and an increased number of GPIO pins from 17 to 36. It also has 16 PWM channels and two cores where each CPU core is managed separately. It also offers an on-chip SRAM with 520 KB of data and instruction storage [96]. These specifications make the ESP32 offer several advantages ranging from power consumption, connectivity options, and analog to digital conversion. The ESP32 has several power modes, including a deep sleep mode that uses a few microamps, to maximize energy efficiency. Additionally, the microcontroller has built-in Bluetooth and Wi-Fi (including BLE), making it ideal for IoT projects and wireless communication without the need for further modules. Furthermore, they enable simultaneous analog input monitoring and offer more accurate analog readings due to multiple ADC channels with a precision of up to 12 bits [95, 97].

4 Applications of Arduino in biosensing

The application of Arduino technology in biosensing represents a significant advancement in the field of biotechnology, offering versatile, affordable, and user-friendly solutions for various diagnostic and monitoring purposes. Arduino's open-source platform, characterized by its accessibility and extensive community support, makes it an

Table 2 Comparison of the specifications of Arduino and competitive microcontrollers

Feature	Arduino	Raspberry Pi	Beagle bone
Microcontroller chip	ATmega328	Broadcom BCM835 SoC full HD multimedia applications processor	TI AM3359
Operating system	Windows, Linux, and Mac OSX	Linux	Linux, Android, Cloud9 IDE on Node.js with BoneScript librar
Central processing unit (CPU)	Atmel AVR (8-Bit), ARM Cortex-M0+	700 MHz Low Power ARM1176JZ-F Applications Processor	1 GHz ARM Cortex-A8
Graphics processing unit (GPU)	Bismuth208/STMGPU	Dual Core VideoCore IV® Multimedia Co-Processor	PowerVR SGX530
Flash memory	32 KB (ATmega328) of which 0.5 KB used by bootloader	32 GB eMMC on-board flash memory	4 GB 8-bit eMMC on-board flash storage
On board storage	SRAM	SD, MMC, SDIO card slot	2 GB 8-bit eMMC on-board ash version microSD card 3.3 V Supported 32 KB
Electronic erasable programmable read-only memory	1 KB (ATmega328)	2 KB	512 MB DDR3 RAM
SRAM	2 KB (ATmega328)	1 GB RAM	1 GHz
Clock speed	16 MHz	1.4 GHz	2 × 46 pin headers
Digital I/O pins	14 (6 of them provide PWM output)	13	1.2 A to 2 A None 20 5 V 5 V
DC current per I/O pin	40 Ma	2 A	USB 2.0 type A 5 V
DC current for 3.3 pin	50 Ma	None	Ethernet RJ45 Male Plug Terminal Block
Analog input pins	6	27	Micro HDMI
Input voltage	Maximum of 12 V	5.1 V	Micro HDMI
Input voltage limit	Maximum of 20 V	5 V	86.40 × 53.3 mm
USB operational voltage	USB cable type A/B, female port A 5 V	Dual USB Connector 5 V	\$95 to \$149
Ethernet	Arduino Ethernet (AVR + W5100)	Onboard 10/100 Ethernet RJ45 Jack	
Audio output	MIDI	3.5 mm jack, HDMI	
Video output	VGA	HDMI	
Board dimensions	69 × 54 mm, 101.52 × 53.3 mm	86 mm × 54 mm × 17 mm	
Price	\$20	\$75	

ideal candidate for developing innovative biosensing devices. This section explores the integration of Arduino into several biosensing techniques, demonstrating how it can enhance functionality, reduce costs, and improve the accessibility of biosensors. In biosensing laboratories, one of the pivotal techniques is the Polymerase Chain Reaction (PCR), which rapidly produces copies of DNA and RNA sequences [99–104]. By incorporating Arduino into PCR devices, researchers have been able to miniaturize and automate the process, paving the way for portable and easy-to-use PoC diagnostic tools. Similarly, Arduino's role in microfluidic devices has shown a potential to reduce costs and improve the precision of fluid control systems, essential for high-performance biomedical research. One significant application of the microcontroller is realized in Loop-Mediated Isothermal Amplification (LAMP), a method used to amplify genetic material for detecting viral infections. Arduino-based LAMP devices offer a portable, battery-operated solution that is cost-effective and easy to use, making them suitable for remote and resource-limited settings [101, 105–108]. Furthermore, Arduino technology has been effectively employed in various types of biosensors, including electrochemical, optical, and thermal biosensors, each contributing to different fields such as medical diagnostics, environmental monitoring, and food safety. This section will delve into the specific applications of Arduino in these biosensing techniques, providing detailed insights into their principles, real-world applications, and case studies. Through these explorations, this review highlights the transformative potential of Arduino technology in making advanced biosensing more accessible and practical for a wide range of users and applications.

4.1 Arduino in polymerase chain reaction (PCR)

One of the techniques used in biophotonic laboratories is the PCR, this technique is used to rapidly produce copies of DNA and RNA sequences [109]. The PCR is used in real time to monitor the amount of DNA along the amplification cycles. This raised the potential to convert the technique to the detection of infectious agents. As a result, a significant amount of attention is directed towards miniaturizing the technique to enable more frequent use [110]. The ideal miniaturized device should possess characteristics of PoC such as being easy to use, such that it does not require trained and special medical personnel to operate it [111]. To achieve this, multiplex-PCR comes out as a solution due to its capability to allow rapid simultaneous detection and quantification of multiple pathogens in different samples [112]. Lim et al. [113] demonstrated the functionality of a multiplex RT-PCR microfluidic chip by subjecting mouse mRNA to a thermal cycler. Their thermal cycler was based on the OpenPCR platform and an Arduino microcontroller to control temperature, the setup is shown in Fig. 5. The Arduino allowed for the implementation of semi-automated, easy-to-use sample-in-answer-out capability for multiplex gene expression analysis. This aligns with the goal of moving from the LoC devices to the PoC devices. The use of Arduino in a PCR has been reported in many studies [99, 102, 104, 114–118], and Table 3 shows some applications. The Arduino microcontroller has been used mainly in PCR to control and regulate temperature to create a PCR cycle [102, 104, 114–117]. However, there have been extensions in using Arduino boards in PCR; Sheu et al. [99] miniaturized a liquid pump that used an Arduino board to push a sample mixture into a chip to implement the PCR process. On the other hand, Angus et al. [118] developed a multiplexed cartridge for low-cost point-of-care diagnostics where the linear actuator was controlled by an EasyDriver motor controlled by an Arduino board for PCR application. The main application of the Arduino boards for the content of this review is to control the temperature for the PCR cycle.

Fig. 5 An illustration of using Arduino boards to measure and control temperature (A) and a prototype developed by Lim et al. (B) [113]. The Arduino microcontroller was used to build the shown in (B) and tested on an RT-PCR assay

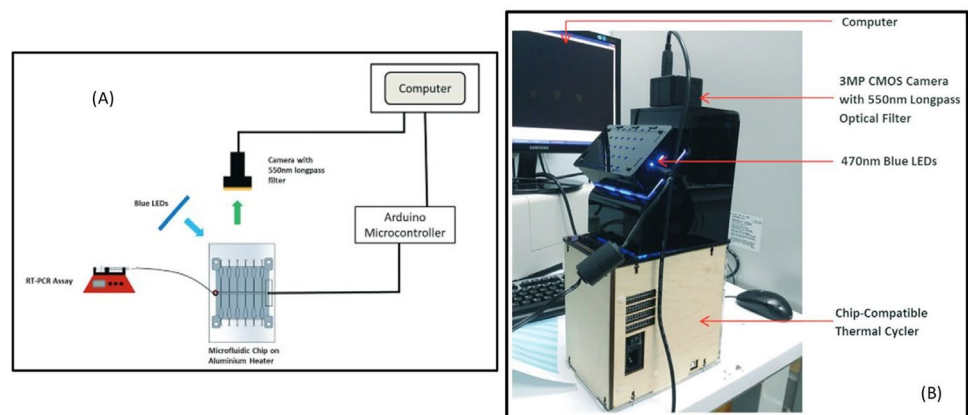


Table 3 Applications of Arduino boards in PCR applications

Research focus	Arduino board type used	Purpose	References
Detecting <i>Colla corii asini</i> with a Portable Continuous-Flow Polymerase Chain Reaction Chip Device Integrated with Arduino Boards	Arduino Mega 2560	Push the sample mixture into the chip to implement the PCR process	[99]
Development of an affordable PCR device utilizing printed circuit board heating for the diagnosis of molecular diseases	Arduino Nano	Heat and cool down the reaction at rates of ~ 2.0 °C/s	[114]
The Smart Controlling-Based Sriwijaya Heat Cycler's Potential as a Tool for DNA Sequence Polymerase Chain Reaction	Arduino Uno	Regulates the length of temperature exposure to the DNA sample	[116]
Reliable, Low-Cost Polymerase Chain Reaction Device for Point-of-Care Medical Diagnosis	Arduino Mega 2560	Control the temperature of the thermal block and lid	[102]
PID Controller with Polymerase Chain Reaction Microchip for Thermal Cycler Design	Arduino nano	Control the temperature to create the PCR cycle	[104]
RPA for low-cost point-of-care diagnostics in the field with a multiplexed cartridge	Arduino Mega	Control the isothermal heater	[117]
An <i>Escherichia coli</i> detection droplet PCR system that is portable, shock-proof, and surface-heated	Arduino Uno	Control the linear actuator from an Easy Driver motor driver	[118]
Plasmonic heating and on-chip temperature sensor integration for amplification of nucleic acids tests	Arduino Uno	Control the plasmonic thermocycler	[115]

4.2 Arduino in loop-mediated isothermal amplification (LAMP)

One of the important experiments for the diagnosis of diseases is to confirm the presence of viral infection in samples. This is done through analytical methods of detecting genetic material such as DNA or RNA [105]. In cases where the number of generic materials is very low to be detected, LAMP is used to amplify these generic materials for detection. The LAMP method is relatively fast, and it is less prone to inhibiting substances [119]. Furthermore, the methods allow for the use of samples without prior purification. Due to these advantages, LAMP serves as an ideal method for PoC analysis [119]. However, real-life applications of LAMP in remote areas as PoC devices are restricted by several factors such as high prices of commercial instruments, not being portable, and complex to be used by untrained personnel [120]. As such, much effort is redirected toward the fabrication of battery-operated devices that are less expensive, portable, and easy to use. This brings much focus to the open electronics microcontroller boards, specifically the Arduino board [61]. Aldrik et al. [105] developed a low-cost, portable, and battery-operated open-source Arduino LAMP shield for DNA detection as shown in Fig. 6. The open-source code operating within the shield allows easy adjustment of temperature and experimental time. This used a prototype shield based on a plug-and-play perforated board to fabricate the Arduino LAMP shield. Although this device performed well by successfully achieving LAMP amplification in 20 min, it suffered from a common limitation of all portable devices i.e., the small size and low capacity of the battery [105]. Therefore, sophisticated architectures are needed for longer-life devices. Based on the reviewed journals in this work, the use of Arduino in LAMP applications was mainly based on controlling the temperature to maintain the reaction temperature required for DNA amplification, capturing the images and data transfer, and illuminating LED lights. Some of the reviewed applications of the Arduino board towards LAMP are outlined in Table 4.

4.3 Arduino in microfluidic devices

Microfluidic systems are a focal point of biomedical research and bioengineering due to their ability to fabricate high-performance components with minimal quantities of reagents and samples [126–128]. However, to control pressure within these systems to offer high performance and pulseless flows with fast responses requires an external pressure source, making them more expensive. The relatively high cost deviated from the realization of LoC systems and applications of the systems in the PoC [128]. Laboratories performing microfluidic-related experiments have continued to work to

Fig. 6 A schematic representation of the Arduino LAMP shield. **a** Electronic connection to the Arduino board, **b** heating coil, **c** and **d** final Arduino LAMP [105]. The shield is used to mount the components to facilitate a LAMP experiment. This allows the shield to be easily used on different Arduino microcontrollers

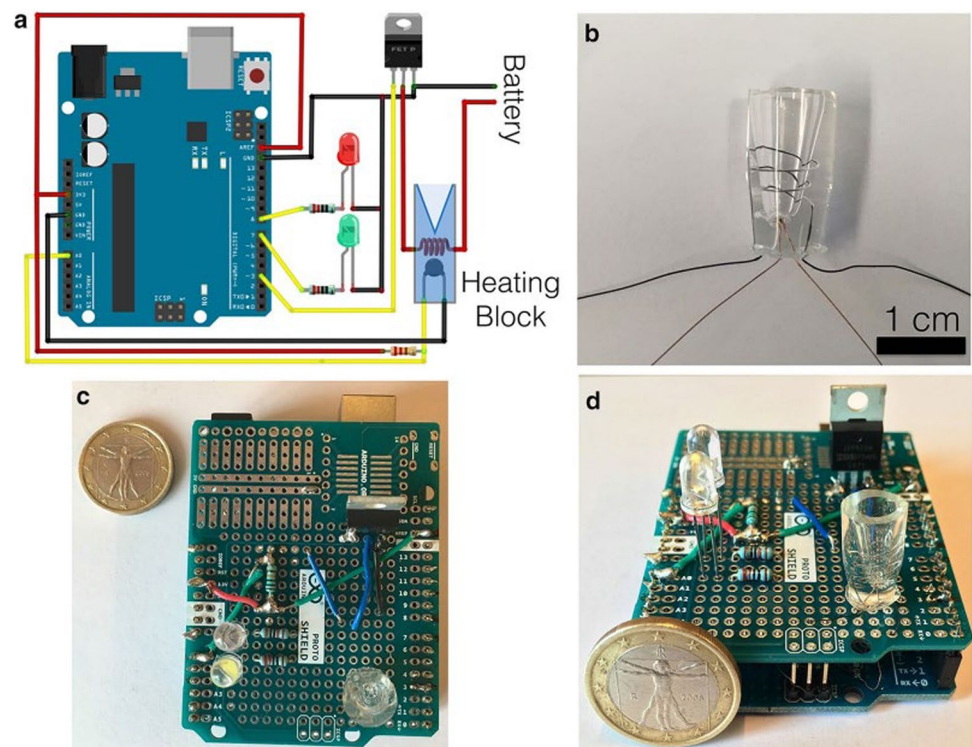


Table 4 Realization of Arduino board in LAMP assay

Research focus	Arduino board type used	Purpose	References
A Loop-Mediated Isothermal Amplification Detection Platform using Digital Microfluidics	Arduino Uno	Temperature control	[121]
On-site nucleic acid testing of pathogens using an integrated CRISPR and loop-mediated isothermal amplification platform on paper	Arduino Uno	Regulating temperature for DNA amplification, managing LED illumination timing, and facilitating data collection,	[122]
Reverse Transcription Loop-Mediated Isothermal Amplification-Based Assay for Lab-on-a-Chip Zika Detection in Point-of-Care Settings	Arduino Uno	To enable on-chip heating capabilities	[123]
Reverse transcriptase loop-mediated isothermal amplification (RT-LAMP) for sensitive nucleic acid detection using a Low-Cost Arduino System	Arduino Nano	Control cooling system	[101]
A compact and economical system for instantaneous isothermal nucleic acid amplification	Arduino Mega	Control of heating system and excitation LEDs	[124]
DaimonDNA: A low-cost, portable loop-mediated isothermal amplification technology for the visual identification of genetically modified organisms in environments with limited resources	Arduino Nano	Switching and amplifying signals to operate the heating system	[125]

build custom syringe pumps to reduce the costs of commercially available syringe pumps [129]. With much of the effort, the use of open-source syringe pumps further decreased the cost. The use of the open-source pumps not only decreased the cost of these systems but also provided an opportunity for these designs to be used worldwide [129]. Lake et al. [128] designed a syringe pressure pump system with the help of an Arduino as shown in Fig. 7. This design consists of four main components: the syringe pump, the pressure sensor and amplifier, the Arduino board, and the motor driver. The success of the design was mainly based on accurate measurements of the fluid pressure inside the microfluidic chip. This was performed from the Arduino board, which in this case measured the voltage of an electrical signal created by a pressure sensor and an amplifier. As a result, it created an easily operated and programmable syringe pump with the advantages of a well-regulated pressure controller [128]. This capability can pave the way for microfluidic systems to realize the goal of transitioning from LoC to PoC. Since then, the use of Arduino boards in microfluidic applications has been realized on a large scale in pressure maintenance in pumps, some of the work is described in Table 5 [128, 130–135]. The use of Arduino to largely control pressure, particularly in microfluidic applications, has been the main realization. As such, in the context of this review, the main use of Arduino is to regulate the pressure in the microfluidic systems.

4.4 Arduino in electrochemical biosensors

Electrochemical biosensors use electrochemical transducers to detect biochemical reactions by converting chemical information into electrical signals [136–141]. These biosensors typically measure changes in current, voltage, or impedance that occur due to the interaction between the analyte and a biological recognition element, such as an enzyme or antibody. Arduino-based electrochemical biosensors are used in a variety of applications, including glucose monitoring for diabetes management, detection of environmental pollutants, and monitoring of food quality [142]. To provide real-time and accurate measurements, Arduino-compatible sensors are integrated with Arduino for data processing and display. An example project that involves an Arduino-based glucose meter that uses an electrochemical sensor to measure blood glucose levels, providing a cost-effective alternative to commercial glucose meters was introduced in [143, 144]. Another project is an environmental sensor that detects chemicals [145] and heavy metals in water using an Arduino-controlled electrochemical cell, offering a portable solution for water quality monitoring.

4.5 Arduino in optical biosensors

Optical biosensors detect biological interactions by measuring changes in light properties, such as absorption, fluorescence, or refractive index. These sensors rely on the principle that biochemical reactions can alter the optical characteristics of a medium, which can then be measured and quantified [146]. Arduino-based optical biosensors are used in medical diagnostics, environmental monitoring, and food safety. For example, they can detect pathogens in water, monitor air quality, and measure the concentration of specific biomolecules in medical samples. One project involves

Fig. 7 A schematic representation of **A** Arduino-controlled pressure in the microfluidic system, **B** the bang-bang algorithm used to control the desired flow pattern, and **C** a representation of a flow pattern [128]. The Arduino in the process regulates and controls the pressure of fluids in a system using a control approach that only uses two states: off (otherwise) and on (when the measurement is below the setpoint)

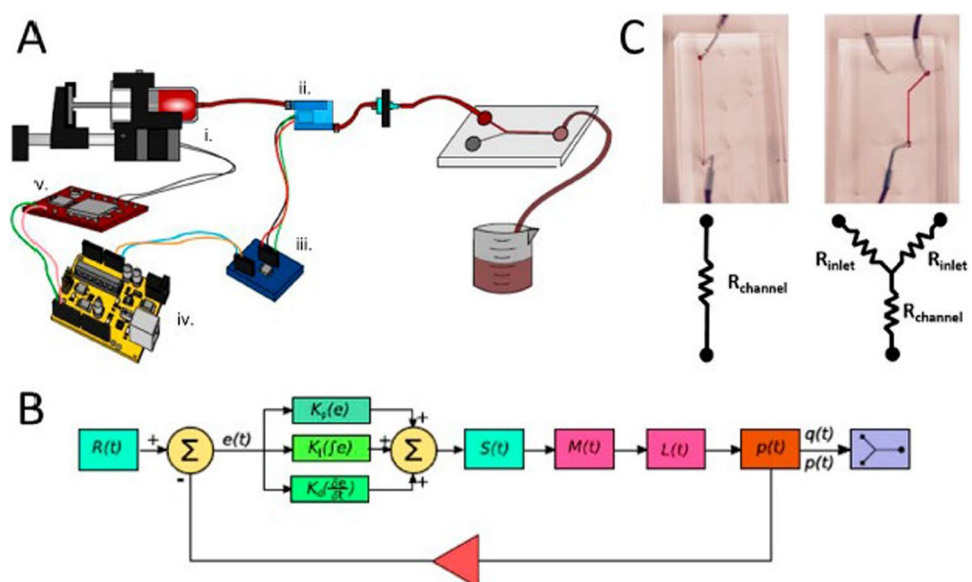


Table 5 Applications of Arduino board in microfluidic systems

Research focus	Arduino board type used	Purpose	References
Developing an Open-Source, Arduino-Based Programmable Multichannel Syringe Pump: A Practical Instrument for Fluid Delivery in Flow Chemistry and Microfluidics	Arduino Uno	Control the injection volume and rate of the syringes	[131]
Syringe pressure pumps with feedback control at a low cost for microfluidic applications	Arduino Uno	Measures electrical signal, with a voltage corresponding to the fluid pressure	[128]
Audistofluidics: open source	Arduino Mega	Control acoustofluidic devices in the audible to low ultrasonic frequency range (31 Hz to 65 kHz)	[132]
Automated Microfluidics-Based Multiplexed Electrochemical Cancer Diagnostic Approach	Arduino Uno	Controls valve actuators, pump, magnetic stirrer, and electronic display	[133]
Cost-effective Droplet Microfluidics using Consumer Opto-Electronic Devices	Arduino Uno	Controlled the mobile lens position	[130]
Metafluidics for open-source, community-driven microfluidics	Arduino Mega	Control solenoids for pneumatic manipulation	[134]
Constant-pressure fluid pump driven by Arduino	Arduino Mega	Stabilize the fluid pressure in systems to maintain constant pressure pumps	[135]

an Arduino-based fluorescence sensor for detecting *E. coli* in water, providing a quick and reliable method for ensuring water safety [147–151]. Another example project uses an Arduino-controlled spectrophotometer to measure the concentration of proteins in a sample, useful for laboratory research and medical diagnostics [147, 148]. Another example looked at the integration of an Arduino microcontroller in the development of a microfluidic device and the immobilized CalB enzyme which were used to establish an optical biosensor for TGs [108].

4.6 Arduino in thermal biosensors

Thermal biosensors detect changes in temperature resulting from biochemical reactions [138, 149, 152–154]. These sensors measure the heat generated or absorbed during a reaction, which correlates with the concentration of the analyte. Arduino-based thermal biosensors are used in medical diagnostics, metabolic studies, and environmental monitoring. They can detect bacterial metabolism, monitor enzymatic reactions, and measure the thermal properties of various substances. An example project involved an Arduino-based thermal sensor that monitors the metabolic activity of bacteria, providing insights into bacterial growth and antibiotic resistance in animals [155]. There is yet another project that uses an Arduino-controlled device to measure the heat produced by enzymatic reactions, offering a tool for studying enzyme kinetics in biochemical research [156–158].

4.7 Arduino with acoustic biosensors

Acoustic biosensors detect changes in the acoustic properties of a medium due to biochemical interactions [159–163]. These sensors measure parameters such as frequency, amplitude, and phase shifts in sound waves. An example case study of an Arduino-based acoustic sensor can detect changes in bacteria like *E. coli* in urine [164].

4.8 Arduino with magnetic biosensors

Magnetic biosensors detect changes in magnetic properties caused by biological interactions [165–169]. These sensors measure variations in magnetic fields, which can be linked to the presence of specific biomolecules. An example project involving an Arduino-based magnetic sensor measures pulsed magnetic resonance of NV centers in diamond [170]. By leveraging the versatility and ease of use of Arduino platforms, these biosensor applications demonstrate the potential for developing innovative, low-cost, and accessible diagnostic and monitoring tools across various fields.

5 Applications of Arduino-based biosensors

Arduino boards are widely used by developers, and innovators to create solutions across various fields. These fields include medical diagnostics, and industrial and environmental monitoring, among others (Fig. 8). Arduino is popular for prototyping in these fields due to its versatility and ease of use. The range of application areas includes system design, general-purpose applications, hardware communication, software prototyping, home and general automation, agriculture, healthcare, mining, energy, defense, and education. Each domain demonstrates the broad utility and adaptability of Arduino in developing innovative solutions. The microcontroller primarily uses sensors to communicate with the real world and obtain digital readings of actual objects to provide solutions to real-world problems. Some of the Arduino-compatible sensors for industrial and environmental applications are shown in Table 5.

5.1 Sensors

A sensor is an apparatus that responds to a quantifiable digital signal after detecting an input stimulus, which could be a quantity, attribute, or condition from the physical world [171, 172]. The response output from a sensor is an electric signal, such as voltage, current, capacitance, resistance, and frequency [173]. There are industry standards to ensure that the sensors meet specified criteria for accuracy, repeatability, and sensitivity. The industry standards for the platinum RTD's (Resistance Temperature Detectors) according to the IEC-751 is $\pm 0.12\%$ of resistance at $0\text{ }^{\circ}\text{C}$, with an accuracy of $\pm 0.3\text{ }^{\circ}\text{C}$ [174]. On the other hand, the Grove-temperature sensor (BME680) compatible with the Arduino microcontroller has an accuracy of $\pm 0.5\text{ }^{\circ}\text{C}$ (Table 5). Another type of sensor in industrial applications is a liquid sensor, by industrial standards, the accuracy of sensors that measure liquid levels is within $\pm 0.12\%$ of the full-scale range [174]. The rain and water level

Fig. 8 This image shows the different areas/fields in which Arduino boards are used by developers, and innovators to create solutions for real-world problems [35]



sensor used in the Arduino project has an accuracy of $\pm 0.25\%$. Therefore, Arduino sensors fall within the acceptable class to be used for various applications.

5.2 Health care

Introducing expert systems has captured researchers' attention to make diagnostics easier and more cost-effective [175]. As such Arduino prototyping in biomedical instruments has shown success in the instruments [176–180]. Various Arduino boards have been used in wearable devices to monitor health status and offer health and safety tips to individuals wearing the device [181, 182]. The application of these devices ranges from temperature monitoring to vital organ monitoring [183]. These applications in health care have been demonstrated in a large context, as shown in Table 6. One of the most widely prototyped, and well-documented medical devices from Arduino is an Electrocardiograph (ECG) Fig. 9, used for medical diagnosis and monitoring [184]. The operation of the device requires a high signal-to-noise ratio and low noise amplification with a high common mode rejection amplifier [185]. However, performing the amplification system remains a challenge because the design is complicated by using discrete electronic components. As part of the solution, many ECG projects have relied on specialized analog front ends with the most popular platform being Arduino® [186–189]. Another wide range of applications for Arduino microcontrollers is realized in wearable devices, where most advanced wearable devices incorporate different sensors because of their low cost. Some of the devices, including the cooperation of Arduino with accelerometers air flow, temperature, and body position sensing, heart rate monitors, and optical heart sensors, are shown in Fig. 10 [179, 181, 190–192].

5.3 Medical diagnostics

Arduino-based systems have been developed for detecting various diseases and biomarkers. These systems use sensors to measure physiological parameters and detect the presence of specific biomarkers, enabling early diagnosis and monitoring of diseases such as diabetes and cardiovascular conditions. Arduino's portability and ease of integration with different sensors make it suitable for creating portable and wearable diagnostic devices.

5.4 Environmental monitoring

Arduino platforms are utilized in environmental monitoring to detect pollutants and toxins in air, water, and soil. These systems use various sensors to measure levels of harmful substances like carbon monoxide, nitrogen dioxide, and heavy metals, helping to ensure environmental safety. Arduino-based systems have been deployed to monitor water and air quality. These systems can measure parameters such as pH, turbidity, temperature, and particulate matter, providing

Table 6 Application of Arduino boards in healthcare

Research focus	Arduino type	Purpose	References
An Arduino based IOT-for human healthcare solution	Arduino Uno	Monitor system for reading and storing patient details using low power for transmitting data	[194]
Healthcare Monitoring System Based on Internet of Things (IoT) Using NodeMCU and Arduino UNO	Arduino Uno	Monitor the patient's physiological parameters by analyzing the signal to detect normal or abnormal conditions	[195]
Real-time Arduino-Based Health Care Monitoring System	Arduino Uno	Supervise the vital signs: temperature, blood pressure, heart rate, gas sensor, and fall detection	[196]
An Internet of Things-based system for tracking patient health	Arduino Uno	Monitor patient with medical care and suggest steps to be followed in case of critical situation	[197]
System for Remote Health Monitoring	Arduino Uno	Sense human vital signs such as temperature, respiration and heartbeat (pulse) in real-time environment	[198]
Wireless patient monitoring system	Arduino Uno	Monitor patients heart rate, body temperature, and saline liquid level; inform doctors and then asks for corrective actions to save patient life	[180]
Cloud-based Real-Time Health Monitoring System	Arduino Uno	Provide body temperature and heart rate	[199]
Health monitoring system based on wires	Arduino Uno	Monitor patient's heart rate, and vital signs. Notify doctors of any abnormalities	[200]
Real-time coal mine worker monitoring system based on LabVIEW	Arduino Uno	Monitor the heart rate, analyze the health condition of workers	[201]
A health monitoring system built on the Internet of Things	Arduino Uno	Monitor the individual's heart rate and body temperature then advise the patient with medical facilitate and the next step to follow in the event of an emergency	[202]
Patient Health Analysis and Monitoring System	Arduino Nano	Measures key health parameters such as heart rate, blood oxygen level, and body temperature	[203]
Developing a technique for measuring body temperature without physical touch	Arduino Uno	Monitor human body temperature (HBT) wirelessly	[204]
Continuous monitoring system for body temperature and heart rate	Arduino Uno	Provide information on heart rate and body temperature simultaneously acquired on the portable device in real time	[205]
Smart health monitoring system with multiple parameters	Arduino Uno	Track patient's cardiac rates and body temperature	[206]
Using Android and IOT, a Modern Healthcare System	Arduino Uno	Automatically gives alarm for patient to take the right medicine at the right time	[207]

Fig. 9 A schematic representation of an Arduino-based broad-board EC prototype. The image shows the prototype developed with Arduino to record the electrical signals in the heart [193]

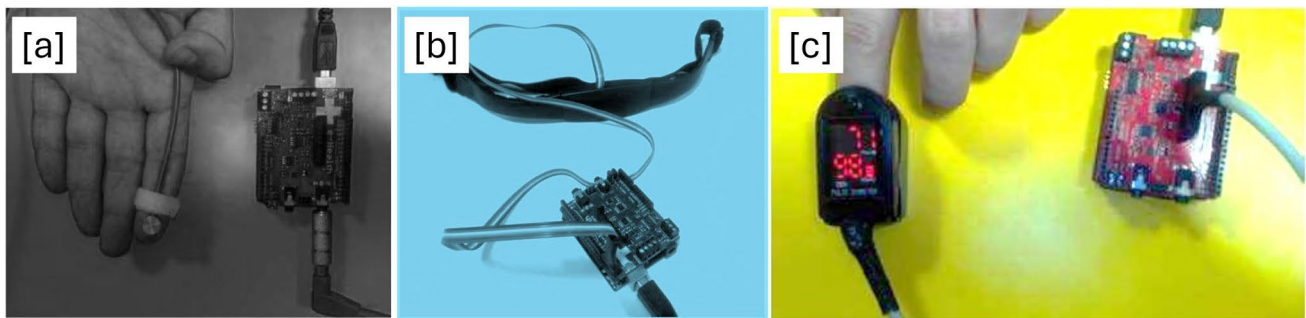
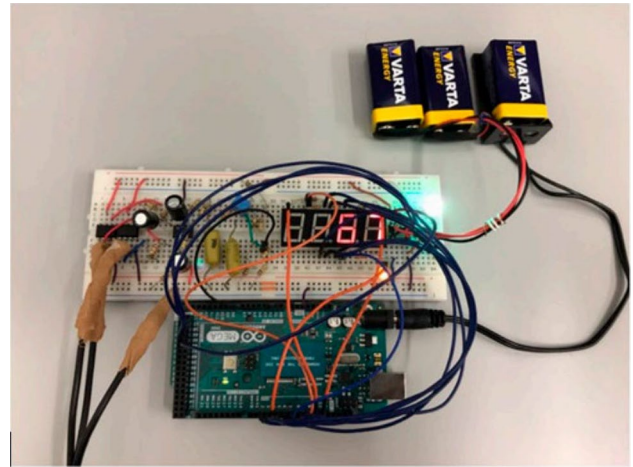


Fig. 10 The wearable devices developed using Arduino microcontroller to measure (a–c) pulse, body position, and temperature sensor [179]. The microcontroller in the applications is used to monitor the heart rate, body temperature, and position through sensors

real-time data for environmental assessment and management. An example project could involve an Arduino-based air quality monitoring system that measures particulate matter and gas concentrations, providing data to alert communities about pollution levels [35]. Another example project could be a water quality monitoring system using Arduino to detect contaminants and ensure safe drinking water [35].






5.5 Food safety

Arduino technology is applied in food safety to detect pathogens and contaminants in food products. Sensors connected to Arduino boards can identify the presence of harmful bacteria, pesticides, and other contaminants, ensuring food safety and quality. Arduino-based systems are used to monitor the quality and freshness of food. These systems can measure parameters such as temperature, humidity, and gas concentrations inside food storage and packaging, helping to maintain optimal conditions for food preservation.

5.6 Industrial monitoring

Arduino is widely used in industrial monitoring to track machine performance, detect faults, and ensure operational efficiency. Sensors connected to Arduino boards can monitor parameters such as temperature, pressure, and vibration, helping to prevent equipment failures and optimize production processes. In research and development, Arduino provides a flexible platform for prototyping and testing new technologies. Researchers use Arduino to develop and refine experimental setups, test hypotheses, and gather data, making it an invaluable tool in various scientific fields. An industrial application can involve using Arduino to monitor the performance of a manufacturing line, detecting anomalies, and improving efficiency (Table 7).

Table 7 Arduino-compatible sensors for industrial and environmental applications

Arduino compatible sensors	Name and use	Accuracy (%)
	Studio Grove-Temperature, Humidity and Pressure (BME680) for Indoor Air Quality Application	Humidity: ±3%r.H Pressure: ±0.6 hPa Temperature: ±0.5 °C
	Rain and water level sensor: measure the water level, monitor a sump pit, detect rainfall, and detect leaks	±0.25%
	Grove—Digital Light Sensor: measures selectable light spectrum ranges from infrared mode, full spectrum to human visible mode	±2 mm
	The pH sensor module: Measures the pH value in liquids	±0.2 PH
	Guva-S12SD Sunlight intensity UV sensor: Detects light range from 240–370 nm	±1UV INDEX

6 Advanced applications of microcontrollers in machine learning

The application of optics and photonics has introduced various methods such as spectrophotometers, lasers, and microscopy for the diagnosis of disease at both molecular and tissue levels to expand the application of PoC devices [208]. Some of the highly important methods to enable PoC technology in Biophotonics include (i) hyperspectral imaging (HIS), (ii) diffusion optical imaging, and (iii) fluorescent markers [209–211]. According to the assumptions, the scattering, absorption, and fluorescent properties of tissues vary as a disease progress [208]. This enables the capture of quantitative diagnostic data from the HIS to enable the interpretation of diseases by machine learning models [208]. On the other hand, more data for machine learning models are generated from the modification of optical properties in 2D topographical datasets from diffusion optical imaging. Significant feature involves the visualization and detection of cells, infected cells, or uninfected cells [208]. This in most cases involves the injection of fluorescent markers into living systems to follow the cell dynamic. The method allows monitoring of cell reactions and, at a specific time, generates parameters to be used as input data from the machine learning technique [208].

Motivated also by the higher accuracy of classifications offered by machine learning algorithms, it is worth coupling the two techniques. Although this is a promising approach, it is a demanding and complex task to be performed, and it has been realized in small applications; especially employing Arduino boards as part of the projects, due to their limitations as mentioned in Sect. 3.7. As such to overcome the limitations brought by the Arduino board, other studies switched to the Raspberry Pi to perform these activities [30]. Archibald et al. [212] built a 3D OpenFlexure delta microscope (<https://openflexure.org/>) based on open-source technology, as shown in Fig. 11 and the specifications of the microscope is shown in Table 6. This microscope offers the advantage of motorized control and maximum stability of the sample during imaging. Together, the images and control of the samples are facilitated by a microcontroller; the images are taken by the Raspberry Pi camera connected to the Raspberry board which at the same time controls the movement of the samples. In this case, the choice of the Raspberry Pi was motivated by its ability to facilitate multiple functions at the same time in opposition to the Arduino as mentioned earlier [212]. Despite the low cost of the device, the microscope as discussed by the OpenFlexure team in Collins et al. [213] offers a versatile imaging capability such as polarization contrast imaging, trans- and epiillumination, and epi-fluorescent imaging. The device also supports algorithms to perform different imaging tasks. For example, in the work of Patton et al. [214] the microscope used a super-resolution radial fluctuations algorithm to obtain images with 115 nm resolution. The biological images collected from the device opened a window of opportunity to incorporate machine learning. That is, Rober et al. [212] classified the biological images from the device using machine learning techniques. Their unique project aimed at implementing a machine learning-based classification

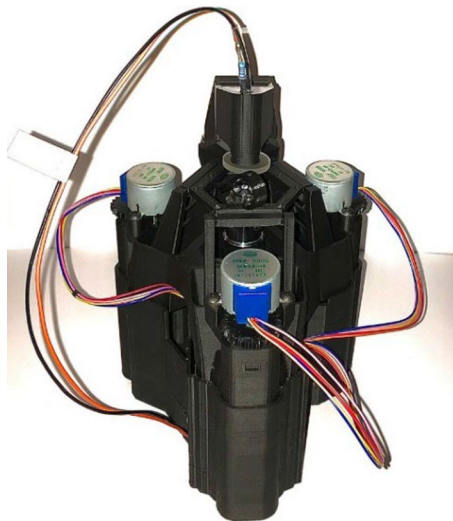


Fig. 11 A representation of a motorized 3D OpenFlexure delta stage microscope. A moving stage of the microscope with sub-micron mechanical placement and good mechanical stability is made possible by the project's 3D printable architecture. The primary benefit of the microscope is that the optics stay stationary, enabling more intricate and substantial optics modes and linking them with external optics. The microscope uses a 5 MP Raspberry Pi camera to capture images at 2560×1440 pixel resolution with a peak classification accuracy of 96.45% [212]

Fig. 12 Classification of images from the motorized 3D OpenFlexure delta stage microscope is done by a type of deep neural network specifically designed to process grid-like data, such as images. A representation of a convolutional neural network used to classify biological images is shown in the image [212]

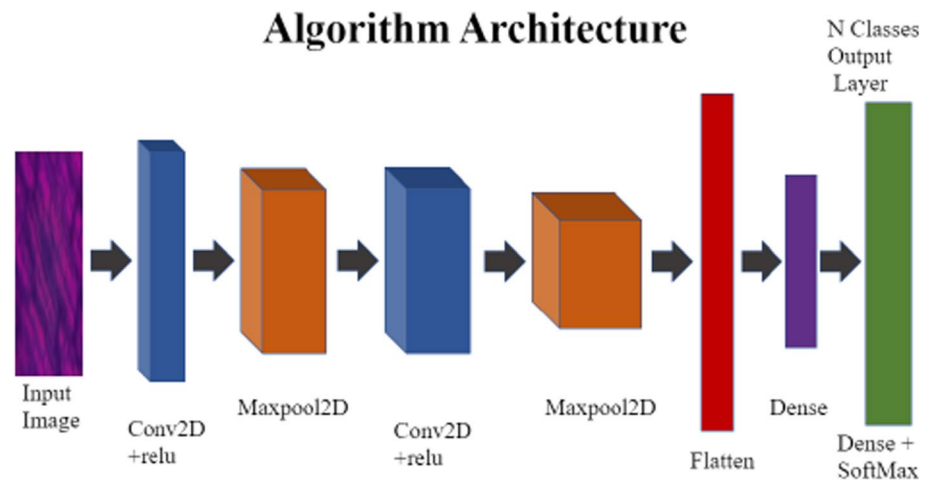


Table 8 Specifications of the 3D open flexure delta stage microscope

3D open flexure delta stage microscope	
Camera	5 MP Raspberry Pi
Image resolutions	2560 × 1440 pixel
Peak classification accuracy	96.45%

approach to biological images taken from the open-source microscope. Images were applied to the multilayered convolutional neural network (CNN) with the architecture shown in Fig. 12. This architecture was made compatible with the microscope by instantiating only two convolutional layers plus the ReLU activation function with two maximum pooling layers that follow the convolutional layers. The output of the model consisted of a flattened layer with two dense layers and a SoftMax activation function. The work achieved a classification accuracy of 99.9% for a training set of images and 99.59% for a testing set of images. The success of the work shows evidence of the efficiency of open-source tools and hence creates even more opportunities for incorporating open-source technology with machine learning algorithms towards the realization of PoC devices (Table 8).

7 Limitations and future prospects of Arduino technologies in biosensing

Whilst Arduino-based technologies offer great potential in the development of affordable technologies, they have several limitations that may need to be addressed. These include processing power and memory constraints, low analog signal resolution, lack of optimization in power consumption, limited integration with advanced sensors, and low scalability and commercial viability [35]. Arduino boards are equipped with microcontrollers that have limited processing power and memory compared to more advanced microprocessors [49]. This limitation can restrict the complexity of biosensing applications, particularly those requiring real-time data processing, large data storage, or sophisticated algorithms. The resolution of ADCs on standard Arduino boards is relatively low (typically 10 bits), which might not be sufficient for applications requiring high precision in signal measurement. This can affect the sensitivity and accuracy of biosensing devices. Arduino boards, while suitable for many applications, may not be optimized for low power consumption. This can be a significant drawback for portable or implantable biosensing devices that require long battery life [215]. While Arduino supports a wide range of sensors, integrating highly specialized or advanced biosensors (such as those requiring high-speed data acquisition or complex signal conditioning) can be challenging. These sensors often demand more sophisticated interfacing and processing capabilities than Arduino can provide. Prototyping with Arduino is ideal for small-scale projects and research, but scaling up to commercial production might require transitioning to more robust and industry-standard platforms. The cost and effort involved in this transition can be a barrier to widespread adoption [35]. Despite these challenges, Arduino does provide a lot of promise and is worth investing in the development of future technologies. There is a lot of potential in the development of the technology. Some advantages include that it can be integrated with ML and AI, the open-source nature of the technology which allows for its development, and it

also has a significant development community. Future iterations of Arduino boards could incorporate more powerful microcontrollers or microprocessors, increased memory, and higher-resolution ADCs. These improvements would expand the range of biosensing applications and enhance the performance and accuracy of biosensing devices. The development of low-power Arduino variants, or improvements in power management techniques, could make Arduino more suitable for portable and wearable biosensing applications. This would extend the usability of these devices in remote or resource-limited settings.

Enhanced support for advanced biosensors, including improved libraries and interfaces, could facilitate the integration of more sophisticated sensing technologies. This would enable the development of more complex and accurate biosensing systems. On the other hand, incorporating advanced wireless communication capabilities (e.g., Bluetooth Low Energy, Wi-Fi, LoRa) and IoT integration would allow Arduino-based biosensing devices to transmit data in real time to remote monitoring systems. This would be particularly beneficial for continuous health monitoring and environmental sensing applications. As the fields of ML and AI continue to grow, integrating these technologies with Arduino platforms could enhance the capabilities of biosensing devices. For example, on-board ML models could be used for real-time data analysis and predictive diagnostics, improving the functionality and effectiveness of biosensors [35]. The thriving Arduino community is a significant asset, providing extensive resources, support, and collaboration opportunities. Continued growth of this community, along with partnerships with academic institutions and industry, can drive innovation and address current limitations in Arduino-based biosensing technologies. The open-source nature of Arduino encourages continuous innovation and customization. As more researchers and developers contribute to the ecosystem, new solutions and improvements in biosensing applications are likely to emerge, further expanding the potential of Arduino technologies. While Arduino technologies have certain limitations in the field of biosensing, ongoing advancements, and the active open-source community offer promising prospects for overcoming these challenges. Therefore, the continued development of Arduino-based biosensing devices has the potential to become even more powerful, accessible, and widely adopted in various fields, including medical diagnostics, environmental monitoring, and food safety.

8 Conclusions

Arduino technology has demonstrated its effectiveness as a versatile and powerful platform for biosensing applications, particularly in medical diagnostics and environmental monitoring. Its integration into biosensing systems enables precise control of essential parameters such as temperature, pressure, and data acquisition, making it indispensable for various detection methodologies. In PCR cycles, Arduino is used to regulate temperature for DNA amplification, while in LAMP assays, it ensures stable reaction conditions, facilitates LED illumination for fluorescence detection, and supports image capture and data transfer. Additionally, Arduino enhances microfluidic biosensing systems by maintaining optimal pressure and fluid flow control. The accessibility, affordability, and open-source nature of Arduino make it a preferred choice for rapid prototyping and custom biosensing solutions. Its extensive community support provides researchers and developers with resources for innovation, while its ease of integration with external sensors and battery-powered applications further enhances its utility. In research and development, Arduino plays a crucial role in designing and testing experimental setups, validating hypotheses, and refining biosensing technologies. Current adoption trends underscore Arduino's significance, with a usage rate of 5.6% in embedded designs and a projected increase to 17% for future implementations. Comparatively, Raspberry Pi and BeagleBone exhibit lower adoption rates, reinforcing Arduino's leadership in open-source hardware platforms for biosensing applications. Moving forward, Arduino's adaptability positions it as a key enabler of advancements in biosensing. As modular components and low-cost sensors continue to evolve, its integration into biosensing systems will drive further innovation in point-of-care diagnostics, environmental monitoring, and industrial applications. Arduino remains the most widely used open-source microcontroller for biosensing due to its versatility, cost-effectiveness, and ease of use. Its role in research, prototyping, and real-world implementation continues to grow, ensuring its relevance in future biosensing technologies.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Ethics and consent to participate Not applicable.

Consent to participate Not applicable.

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