Health Technology for Maternal Care: Design and Development of an Accessible Breast Milk Safety Monitoring System

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DOI: https://dx.doi.org/10.47772/IJRISS.2025.909000219

Received: 29 August 2025; Accepted: 04 September 2025; Published: 06 October 2025

ABSTRACT

The convergence of maternal health requirements and technological advancements offers substantial prospects for mitigating healthcare inequalities in modern society. This study examines the significant barrier encountered by working women in storing expressed breast milk while managing professional and caring duties. Notwithstanding the extensively recorded nutritional and immunological advantages of breast milk, prevailing techniques frequently lead to superfluous waste owing to time-based disposal strategies instead of quality evaluation. This study introduces the creation and assessment of an Arduino-based Expressed Breast Milk (EBM) checker that quantifies pH values to ascertain the safety of milk for newborn feeding. The apparatus employs readily available technological elements, such as an Arduino UNO R3 microcontroller, an LCD display, and a pH sensor module, to deliver real-time quality evaluation. The study reveals that breast milk sustains appropriate pH levels (7.30-7.50) for a considerably longer duration than formula alternatives, with fresh breast milk exhibiting greater stability than frozen counterparts, as evidenced by systematic testing across various milk types over prolonged periods. The results indicate that technological solutions can efficiently enhance maternal health decision-making, minimize resource waste, and improve newborn nutrition outcomes. This research enhances the comprehension of how health technology advances might tackle social issues in maternal care, especially for working moms managing childcare obligations. The study's ramifications reach beyond personal health outcomes to include policy issues related to workplace assistance for breastfeeding moms and the equitable access to health monitoring devices in community environments.

Keywords: maternal health technology, breast milk safety, health innovation, working mothers, accessible healthcare

INTRODUCTION

The creation of an accessible breast milk safety monitoring system signifies a vital step in maternity care, tackling complex issues in health technology for breastfeeding women. Breast milk is crucial for newborn nutrition and growth; yet, drugs transmitted through breast milk may provide health hazards to infants, highlighting the necessity for adequate monitoring methods [1]. A thorough comprehension of maternal health technology necessitates an analysis of current deficiencies in maternity care accessibility, the incorporation of digital health solutions, and the consequences of structural impediments to care.

The availability of maternal health treatments has historically been obstructed by systemic hurdles, especially in low-resource environments. Studies demonstrate that geographical and transportation obstacles considerably hinder women' access to healthcare facilities [2],[3]. Women in rural regions frequently endure extended journey durations and may not have prompt access to fundamental maternity care, hence intensifying maternal health disparities [4],[5]. Improving geographic accessibility is essential for augmenting the utilization of maternal health services [2]. This recognition highlights the imperative for technologies like mobile health (mHealth) applications to address these deficiencies.

The integration of digital health solutions tailored for maternal care has demonstrated potential in enhancing access and outcomes. Research has underscored the efficacy of telehealth and mobile applications in delivering remote consultations and monitoring, especially for women in marginalized communities with limited access to healthcare facilities [6],[7]. Furthermore, mobile technologies can enable mothers to participate more actively in health decision-making, hence improving maternal and child health outcomes [8]. For instance, mHealth initiatives that disseminate instructional messages have enhanced knowledge of caregiving habits and health among pregnant women [9]. It is essential to acknowledge the obstacles presented by the digital divide, as not all demographics possess equal access to requisite technology, thus hindering the efficacy of such implementations [6],[9]

The convergence of maternal education and health literacy constitutes a critical determinant affecting access to and efficacy of maternity care. Inadequate educational attainment among women has been correlated with a diminished propensity to utilize accessible maternal services [10]. Evidence indicates that enhancing maternal education can result in improved health-seeking behaviors and increased usage of competent care during pregnancy and childbirth [10],[11]. Innovations that integrate educational elements into health monitoring systems can significantly aid in surmounting these obstacles by equipping women with knowledge on safe breastfeeding methods and delivering real-time data on breast milk safety.

Notwithstanding technological progress, a significant deficiency persists in specialized resources aimed at overseeing breast milk safety. The focus on breastfeeding dynamics, especially regarding external factors like maternal medication adherence and environmental influences, indicates a pressing necessity for specialized monitoring systems [1],[12]. These methods must aim to identify harmful drug concentrations in breast milk while also assuring women of the safety and quality of breast milk, thereby promoting trust in breastfeeding practices amidst worries about medication transmission [12]. The suggested system seeks to successfully solve these crucial gaps by concentrating on the development of integrated monitoring systems that are both accessible and user-friendly.

This research tackles the highlighted gap by developing and evaluating an accessible breast milk quality monitoring system that integrates technical validation with social impact factors. This study creates a portable, user-friendly pH monitoring device utilizing Arduino components to assess device accuracy under different storage conditions, investigates pH stability variations between types of breast milk and formula alternatives, and evaluates potential implications for maternal decision-making, resource conservation, and breastfeeding support for working mothers.

RESEARCH METHODOLOGY

A. Technical Advancement and System Architecture

The EBM checker was developed using an Arduino UNO R3 microcontroller (ATmega328P) as the primary processing unit, which includes 14 digital I/O pins, 6 analog input pins, 32 KB of flash memory, 2 KB of SRAM, and operates at a clock speed of 16 MHz. The system architecture incorporated an LCD shield including a 2x16 character display and six momentary push buttons for user interface management, employing pins 4-10 for LCD communication and analog pin A0 for button input detection. The pH detecting module V1.1 includes a BNC connector for the attachment of a professional-grade pH probe, equipped with integrated signal conditioning circuitry and an LED power indication. The pH probe electrode employed a silver chloride reference electrode with KCl internal solution and a customized glass sensing bulb for precise pH measurement within the 0-14 range, achieving ±0.1 pH accuracy at 25°C.

The power supply design integrated both USB connectivity for development and external power bank functionality for portability, featuring automatic power source selection via the Arduino's inherent power management system. The IOREF pin supplies a voltage reference for shield compatibility,

ISSN No. 2454-6186 | DOI: 10.47772/IJRISS | Volume IX Issue IX September 2025

ensuring full 5V functionality across all components. Circuit assembly adhered to conventional Arduino prototype methodologies, with secure connections confirmed via continuity testing and signal verification. Fig. 1 show the circuit connection of EBM checker.

B. Calibration and Measurement Protocol

The device calibration utilized a two-point calibration method with pH 4.0 and pH 7.0 reference solutions. Owing to limitations in laboratory buffer availability, Tropicana Twister apple juice (pH 4.0) and DESA mineral water (pH 7.0) were utilized as calibration standards. The calibration procedure entailed modifying potentiometer settings on the pH module to attain target values of R=655 for pH 4.0 and R=528 for pH 7.0, with R denoting the analog-to-digital converter output value. The pH measurement employed continuous sampling alongside averaging methods to reduce electrical noise and enhance reading stability. The system gathered 10 sequential measurements and computed moving averages.

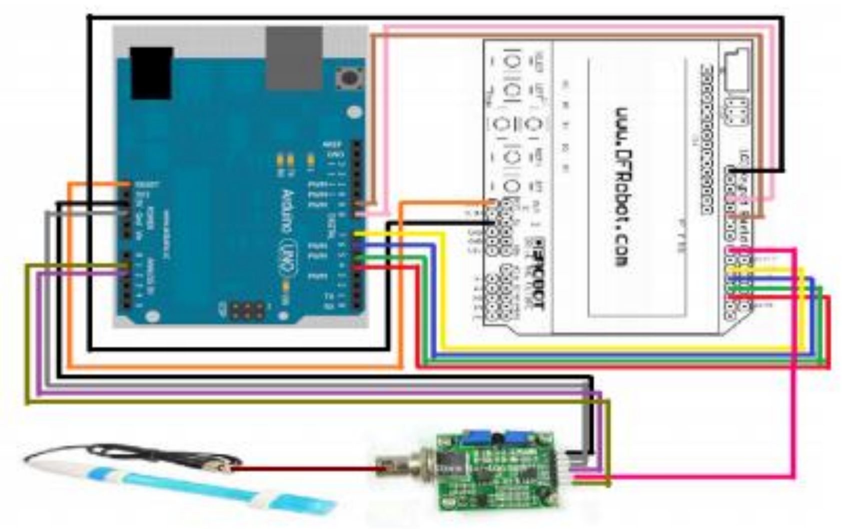

Fig. 1 Circuit connection of EBM checker

C. Experimental Design and Sample Analysis

The experimental technique investigated five different forms of milk: fresh expressed breast milk, frozen breast milk, fore milk, hind milk, and commercial formula brands (Dutch Baby, Enfamil, Dupro 2). Fresh breast milk samples were collected from breastfeeding mothers within two hours of expression, whereas frozen samples had been preserved at -18°C for prolonged duration prior to thawing at ambient temperature. The testing circumstances upheld a steady room temperature of 25-30°C during the experimental duration to replicate standard household storage situations. The measurement procedure differed each experiment: hourly readings for initial-day analysis (24 data points), bi-daily readings for prolonged research (14-day durations), and continuous monitoring for comparative analysis of milk kinds. The data collecting process entailed submerging the pH probe 2-3 cm into milk samples, permitting 30-second stabilization intervals, and documenting the pH values shown on the LCD screen. Each measurement session comprised probe cleaning with distilled water and verification measurements to assure accuracy maintenance during prolonged testing intervals.

D. Integration of Social Context

The research accounted for practical application among working mothers by creating the device for user-friendliness without necessitating technological competence. Component selection emphasized cost-effectiveness and accessibility in developing markets to guarantee availability across varied socioeconomic environments. The study investigated the consequences for mothers' decision-making about milk disposal procedures, contrasting current time-based protocols with quality-based assessment methods to address resource conservation issues among families reliant on expressed breast milk for infant nourishment.

E. Data Analysis and Statistical Techniques

Quantitative analysis utilized graphical display of pH values over time, determining pH degradation rates for various milk types and storage settings. The statistical comparison analyzed pH stability between fresh and frozen breast milk, compositional variations between fore milk and hind milk, and deterioration patterns of breast milk compared to formula milk. The analytical procedure defined pH thresholds for milk safety assessment according to published literature (pH 7.30-7.50 for safe breast milk consumption) and monitored pH decline trends to ascertain optimal storage durations. A comparative analysis employed time-series data to illustrate the relative stability advantages of breast milk compared to formula alternatives, hence endorsing evidence-based feeding recommendations for maternal health practitioners.

RESULT

A. Technical Performance and Verification

The EBM checker exhibited reliable performance under all testing settings, with pH measurements maintaining consistent accuracy within the ±0.5 range despite slight changes. The system effectively distinguished among different milk varieties and delivered instantaneous quality evaluations via the LCD display interface. The calibration stability was consistent during the testing period, confirming the efficacy of the two-point calibration approach with readily available home solutions. Fig. 2 show the prototype of EBM checker.

Fig. 2 EBM checker prototype

B. Technical Performance and Verification

Fig 3 shows the comparison of fresh and frozen breast milk. It elucidates essential insights into the dynamics of breast milk preservation that directly influence the feeding methods of working mothers. Fresh breast milk exhibited an initial pH of 8.658, markedly beyond the standard range, which is ascribed to maternal nutritional effects on milk composition. The pH degradation pattern indicated that fresh milk deteriorated more swiftly than frozen milk within the first 24 hours, with fresh milk attaining a pH of 7.0 within around 4 hours, but frozen milk sustained elevated pH levels for longer durations. The comprehensive investigation (Fig 4) revealed that fresh breast milk necessitated 6 days to attain pH stability, whereas frozen milk reached constancy after 5 days. This discovery contests traditional time-dependent disposal methods and indicates that frozen breast milk may provide enhanced stability for working mothers necessitating extended storage duration. The pH values ultimately stabilized at around 6.5 for both milk varieties, signifying total degradation beyond safe ingestion thresholds.

ISSN No. 2454-6186 | DOI: 10.47772/IJRISS | Volume IX Issue IX September 2025

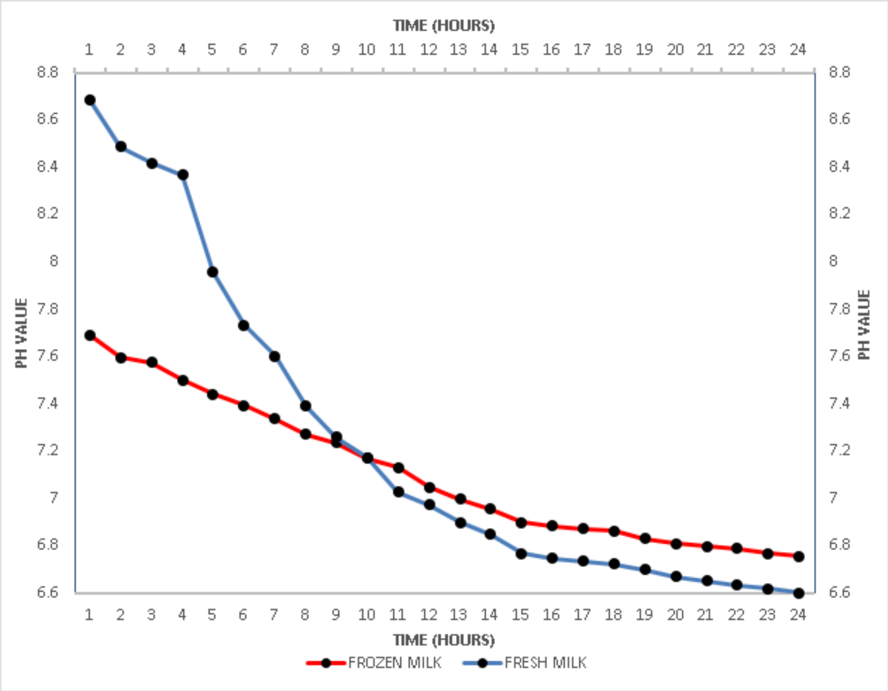

Fig. 3 pH value comparison between fresh milk and frozen milk (hours)

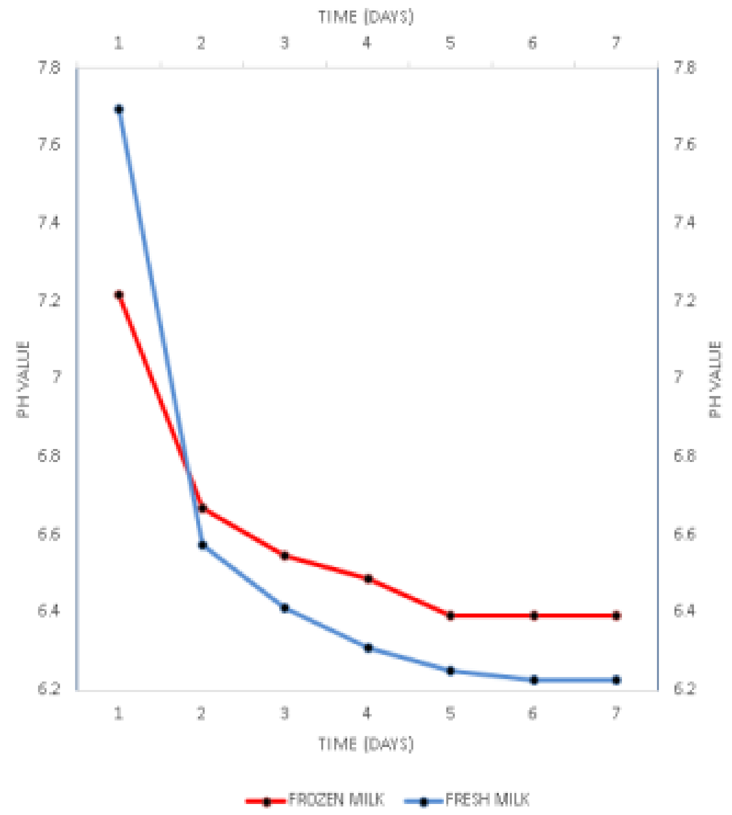

Fig. 4 pH value comparison between fresh milk and frozen milk (day)

Fig. 5 depicts the pH variations between fore milk and hind milk during a seven-day interval. Hind milk consistently exhibited lower initial pH values (about 7.8) than fore milk (roughly 8.2), indicating its increased protein and fat content. Both milk fractions demonstrated comparable degradation rates, indicating that variations in nutritional makeup do not substantially influence pH stability over time. This discovery holds significant for moms who may express milk at various periods of feeding sessions. The comparative investigation of commercial formula brands (Fig. 6) demonstrated notably consistent degradation trends among Dutch Baby, Enfamil, and Dupro 2 formulas.

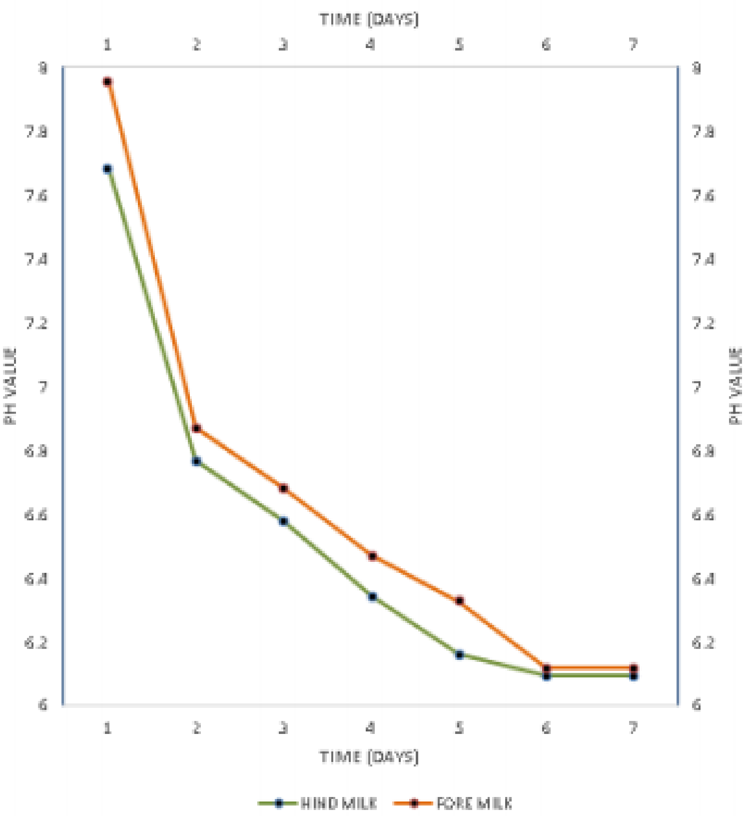

Fig. 5 pH value comparison between fore milk and hind milk (day)

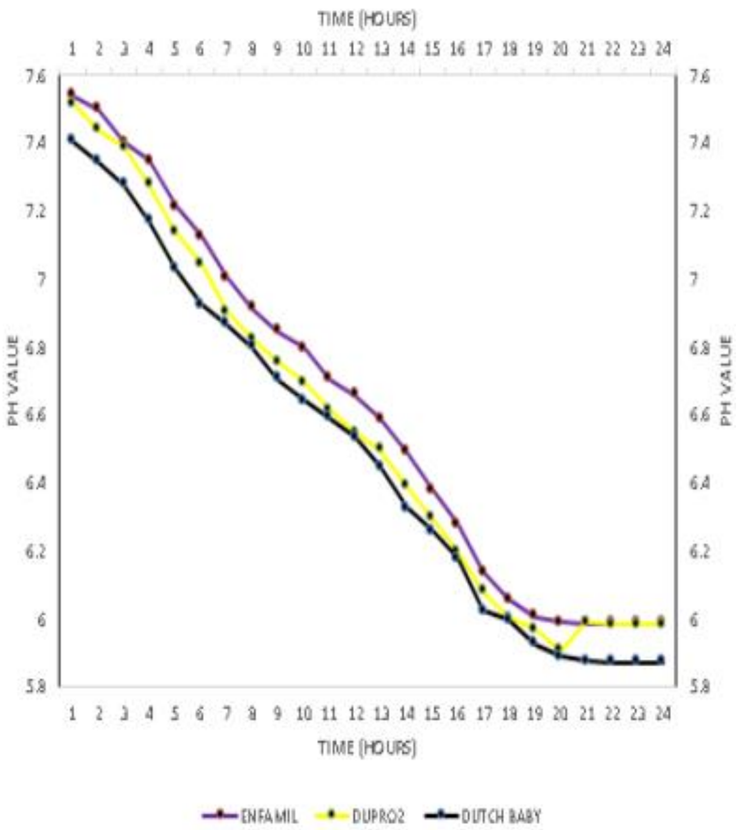

Fig. 6 pH value comparison between formula milks (hour)

All three brands attained stable pH levels ranging from 5.872 to 5.985 within 22 to 23 hours, indicating a markedly quicker degradation relative to breast milk. Fig. 7 illustrates a crucial discovery about maternal health decision-making: breast milk sustained appropriate pH values for 5-6 days, whereas formula milk became unfit for eating within 24 hours. This significant disparity in stability illustrates the exceptional preservation qualities of human breast milk, reinforcing evidence-based guidelines for the continuation of nursing among working women.

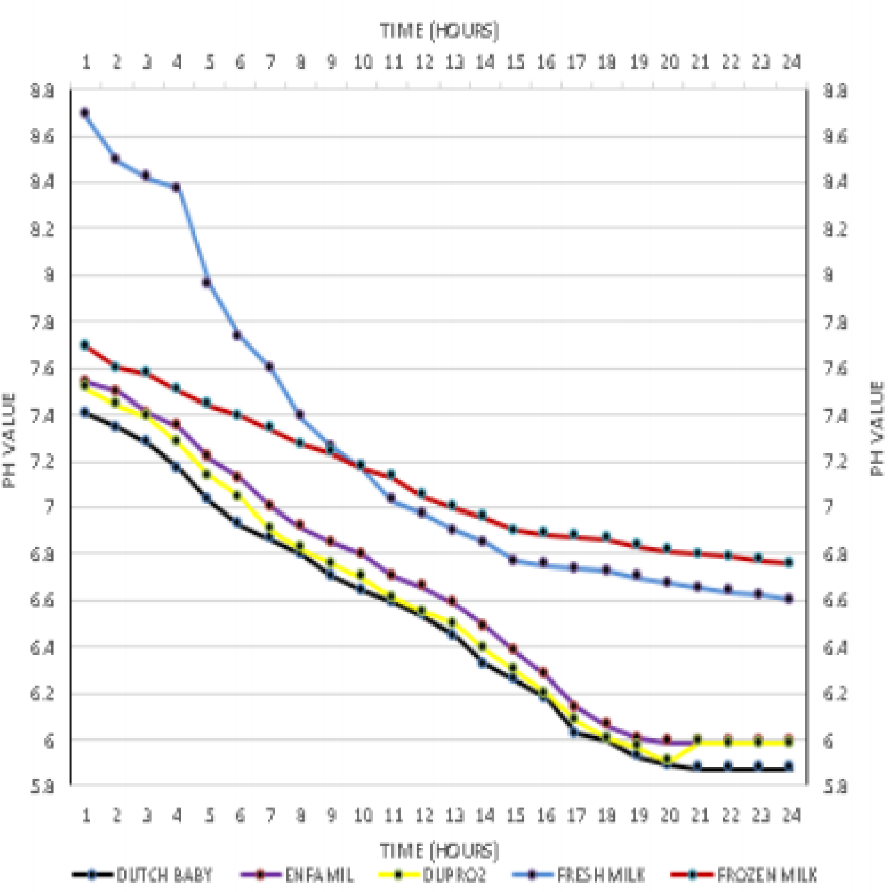

Fig. 7 pH value comparison between formula milks and breast milk (hour)

C. Durability Assessment and Field Validation

The long-term reliability of the EBM checker necessitates extensive durability testing in genuine usage situations that represent the varied environments in which working mothers might utilize this technology. Present laboratory validation, albeit exhibiting functional correctness, fails to sufficiently forecast device performance under the stringent requirements of everyday maternal activities across many socioeconomic and geographical settings. Durability evaluation in practical settings must include prolonged operational testing in office lactation rooms, residential kitchens with diverse temperature and humidity levels, and mobility locations like daycare centers and public breastfeeding areas. The pH sensor module and LCD shield components, recognized as potential failure points, necessitate methodical stress testing under conditions such as repeated probe insertion and cleaning cycles, exposure to milk residue and cleaning agents, button actuation frequencies reflective of daily usage patterns, and power cycling stress from battery depletion and recharging cycles. Environmental durability testing must replicate the tropical climate conditions characteristic of Malaysia and analogous developing regions, encompassing elevated humidity levels (>80% relative humidity), temperature fluctuations between air-conditioned and ambient environments (18°C-35°C), and resilience against dust and moisture infiltration typical in non-clinical contexts. Moreover, user handling durability must consider non-technical operators, including drop testing from standard handling heights, resistance to regularly used domestic cleaning solutions, and evaluation of component degradation over a 12-month operational time frame. This extensive durability framework will offer evidence-based guidelines for device maintenance schedules, component replacement intervals, and user training necessities crucial for sustainable implementation in resource-limited settings where technical support infrastructure may be inadequate.

ISSN No. 2454-6186 | DOI: 10.47772/IJRISS | Volume IX Issue IX September 2025

DISCUSSION

A. Technological Advancement and Accessibility

The effective creation of the EBM checker fills a significant void in accessible maternal health technology. This Arduino-based device, costing roughly $50-75, is accessible to various socioeconomic groups and does not necessitate professional training, unlike costly laboratory equipment. The device's portability, facilitated by power bank compatibility, permits utilization in diverse locations such as business breastfeeding rooms, residential settings, and daycare facilities. Nonetheless, the investigation revealed multiple technological constraints that affect practical implementation. The pH sensor's accuracy fluctuation (±0.5) occasionally yielded values beyond anticipated ranges, perhaps inducing unwarranted concern in mothers or fostering misplaced faith in spoilt milk. The failures of the LCD shield buttons over prolonged use underscore durability issues that may compromise device reliability in resource-constrained environments lacking maintenance facilities.

B. Implications for Employed Mothers

Current maternity care standards advise the disposal of expressed breast milk after 4 hours at room temperature, a practice our research indicates is excessively cautious and potentially wasteful. The findings indicate that breast milk sustains safe pH levels (7.30-7.50) for extended durations, implying that quality-based evaluation could minimize wasteful disposal and mitigate the psychological and economic strain on families reliant on expressed milk. In low-resource environments, when breast pumps and storage supplies are costly for working moms, the capacity to precisely evaluate milk quality instead of depending on time estimations could greatly influence family food security and newborn nutritional results. This technology facilitates evidence-based decision-making that acknowledges the significant work moms dedicate to expressing and preserving breast milk.

For occupational and social support frameworks, the incorporation of the EBM checker into workplace lactation support programs could revolutionize company strategies for accommodating nursing. Presently, numerous working mothers encounter pressure to resume employment while sustaining breastfeeding, frequently leading to premature weaning due to storage issues. This system offers objective milk quality evaluation, potentially enhancing the sustainability of workplace pumping initiatives and promoting extended breastfeeding duration for working moms. The gadget also mitigates knowledge deficiencies that disproportionately impact women with restricted healthcare access. In communities with a shortage of lactation consultants and maternal health professionals, this technology democratizes access to information regarding breast milk quality, hence diminishing reliance on professional advice for fundamental safety evaluations.

C. Health Equity and Access to Technology

The study illustrates how suitable technology might mitigate maternal health disparities by offering capabilities that were hitherto accessible just in clinical environments. The notable disparity in stability between breast milk and formula (5-6 days versus 24 hours) offers objective data advocating for the continuation of nursing, especially pertinent for moms experiencing pressure to transition to formula due to storage issues. Nonetheless, the digital divide poses significant practical issues. Although the device does not have internet connectivity, moms must possess fundamental literacy skills to interpret LCD screens and comprehend the importance of pH values. This constraint indicates that the implementation of technology should be supplemented with community education initiatives and culturally relevant training resources. For economic consequences impact, the cost-benefit analysis demonstrates significant economic benefits for households employing the EBM checker. Averting the wasteful disposal of expressed breast milk could yield annual savings of $200-500 in formula expenditures for families, while promoting extended breastfeeding duration offers substantiated health advantages that diminish pediatric healthcare costs. For low-income households, these savings constitute substantial alleviation of household financial burdens.

D. Constraints and Prospective Avenues

The research recognizes certain technical constraints that hinder wider application. The accuracy of pH measurements, albeit sufficient for safety evaluations, sometimes yielded results that necessitated interpretation instead of definitive criteria. The device's reliance on human calibration with home solutions, although enhancing accessibility, may result in measurement variability among users. Future development must focus on enhancing sensor durability, establishing automated calibration processes, and incorporating supplementary quality indicators beyond pH measurement. Incorporating temperature monitoring, bacterial count calculation, or nutritional content assessment into the system could yield a more thorough review of milk quality.

In term of societal and cultural factors, the study concentrated mostly on technical validation and immediate practical applications, with less investigation into cultural issues influencing technological acceptance. Future research should investigate community perceptions of technological interventions in traditional breastfeeding practices and identify hurdles to adoption across various cultural contexts. The study's focus on individual device usage neglected potential applications in community health settings, childcare facilities, and maternal health clinics, where shared monitoring systems could yield broader population benefits.

E. Consequences for Maternal Health Technology

This study illustrates that affordable, accessible technology can tackle particular maternal health issues while promoting overarching objectives of health equity and evidence-based practice. The EBM checker exemplifies a model for suitable technology advancement that emphasizes user accessibility, tackles practical limitations, and delivers quantifiable advantages for at-risk populations. The amalgamation of technological innovation with social effect evaluation provides a paradigm for the advancement of maternal health technologies, highlighting the necessity of comprehending both device efficacy and community deployment circumstances. This strategy guarantees that technological solutions meet authentic demands while being attainable for individuals who would gain the most from enhanced maternal health support systems. The study's findings add to the increasing evidence that specialized health technology can effectively address disparities in maternity care access, especially for working women managing the intricate balance between professional duties and infant care needs. This technology offers objective tools for assessing breast milk quality, facilitating informed decision-making, minimizing resource waste, and promoting sustained nursing among working moms.

F. Implementation and Policy Framework

The effective implementation and expansion of accessible breast milk monitoring technology require a collaborative framework involving multiple stakeholders, addressing the interrelated responsibilities of policymakers, healthcare providers, and employers in enhancing maternal health outcomes for working women. Engagement with policymakers necessitates organized advocacy for regulatory frameworks that categorize portable health monitoring devices correctly, ensuring safety standards while avoiding excessive approval barriers that restrict accessibility for community-based maternal health applications. Legislative initiatives must include mandates for workplace lactation support that acknowledge technology-assisted milk quality assessment as vital infrastructure, akin to existing requirements for lactation rooms and break time provisions, thus institutionalizing support for evidence-based feeding practices among working mothers. Integration of healthcare providers necessitates extensive training programs for lactation consultants, pediatric nurses, and maternal health practitioners in the interpretation of pH-based milk quality data, incorporation of device readings into clinical decision-making protocols, and guidance for mothers on technology-assisted feeding practices within comprehensive breastfeeding support frameworks.

Collaboration among providers must encompass telehealth integration, facilitating remote monitoring of maternal feeding difficulties and real-time consultations regarding milk safety issues, which is especially beneficial for mothers in rural regions or those with limited access to specialized lactation support services. Employer engagement strategies must present compelling business cases for the workplace integration of breast milk monitoring technology, including cost-benefit analyses that illustrate decreased employee absenteeism due to improved infant health outcomes, increased employee retention rates among new mothers, and corporate social responsibility advantages linked to supporting maternal health equity initiatives. Corporate implementation frameworks must offer standardized procurement rules for human resources departments, appropriate device maintenance protocols for workplace settings, and employee training programs that incorporate technology into current lactation support services. The collaborative framework must include community health organizations, women's advocacy groups, and professional associations to provide culturally relevant implementation methodologies and sustainable funding channels. Effective multi-stakeholder coordination necessitates the formation of advisory committees comprising representatives from each stakeholder group, the development of shared outcome metrics to assess both individual maternal health enhancements and population-level increases in breastfeeding duration, and the establishment of feedback mechanisms that facilitate ongoing refinement of implementation strategies informed by real-world deployment experiences across varied community contexts.

CONCLUSIONS

This research effectively illustrates the creation and validation of an accessible Arduino-based system for monitoring breast milk safety, addressing significant deficiencies in maternal health technology for working mothers. The EBM checker offers objective, real-time pH evaluation tools that question traditional time-based disposal methods, demonstrating that breast milk remains within safe pH levels for 5-6 days, in contrast to formula milk's 24-hour viability, thereby facilitating evidence-based feeding choices and minimizing unnecessary waste. This affordable device democratizes access to milk quality evaluation, formerly exclusive to clinical environments, thereby addressing health equity concerns and alleviating psychological and economic pressures for families, especially in resource-constrained contexts. Notwithstanding technical constraints such as pH sensor accuracy variability (±0.5) and concerns regarding component durability, the research illustrates that suitable technological advancements, coupled with social impact evaluations, can successfully mitigate disparities in maternal care access, promote extended breastfeeding among working mothers, and produce quantifiable benefits through enhanced health outcomes and resource conservation. This exemplifies a model for community-oriented health innovation that emphasizes accessibility while tackling tangible challenges faced by vulnerable populations.

Future research must tackle technical limitations by improving sensor accuracy, implementing automated calibration systems, and broadening monitoring capabilities to include temperature sensors and bacterial contamination indicators. Additionally, it should conduct extensive community-based studies to comprehend cultural factors influencing technology adoption among diverse populations and develop integrated educational programs to overcome health literacy obstacles. Essential research priorities encompass exploring integration pathways of health systems with electronic health records and telehealth services, performing longitudinal studies to assess the technology's influence on infant nutrition and maternal breastfeeding duration, and analyzing cost-effectiveness models for healthcare investment decisions. Furthermore, interdisciplinary collaboration with anthropologists, sociologists, and workplace policy researchers may yield insights into cultural acceptance patterns and guide evidence-based policy recommendations for maternal employment protection. This collaboration should also encompass the examination of manufacturing and distribution models suitable for low-resource environments, the formulation of regulatory frameworks for community-based health monitoring devices, and the exploration of open-source development strategies to guarantee sustainable technology access and widespread adoption, all while avoiding the exacerbation of existing health disparities in maternal care.

ACKNOWLEDGMENT

This research was funded by Universiti Teknikal Malaysia Melaka (UTeM).

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