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Review Article

FRUGAL SCIENCE INNOVATIONS: PROMISING TOOLS FOR EDUCATION AND HEALTHCARE

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ABSTRACT

In recent years, emphasis is being given to frugal affordable and sustainable innovations. This article advocates the potential of frugal products characterised with robust product functionality especially in low resource settings in the healthcare and education sectors so that benefits of science can reach the masses. Frugal innovation does not mean compromising the quality, but it is to be able to apply science to get the desirable result in the given conditions. The article discusses some recent innovative frugal products and their comparisons to conventionally used technologies. It elaborates on two innovations, Foldscope and Paperfuge which are frugal alternatives to microscope and centrifuge respectively with potential applications in diagnostics, research, and education especially in developing economies.

Keywords: Frugal, Paperfuge, Foldscope, Education, Healthcare.

1. INTRODUCTION

Over the past few years, with the advancement in science and especially in the field of biomedical research, scientists have shifted their focus to frugal products, as most of the devices or equipment used in the diagnosis or analysis are highly expensive and bulky. The cost is mainly attributed to the raw material used in manufacturing of these devices. The skilled manpower needed for its operation further shoots up the costs. This enormously high cost of equipment constrains its use due to limitation of materialistic support to the students, researchers, and organisations. There is only about 1% of the population in the world that can afford quality diagnostics and rest cannot afford due to the high costs. Lack of infrastructure, trained personal, low capacity and less capable distribution channel also renders the use of highly sophisticated medical and research devices limited [1]. Considering the examples of Magnetic Resonance Imaging (MRI) and electron microscope, both the devices though extremely useful for medical imaging and research are extremely costly with additional load of high one-time operational cost and recurring maintenance cost, limiting its use [2]. The expensive nature of such devices renders it inaccessible to a major section of the society. This has led to a strong income-based segregation of health care and research facility received by an individual. Most devices require a constant supply of electricity due to which these facilities are mostly concentrated in the urban settings, thus depriving the rural settings from availing its benefits which is the base for the health care [3]. These so called power-hungry devices have been manufactured only to work in high resource settings of developed countries with electrical power grids. Recently during the pandemic crisis, countries especially the developing economies have felt the need and identified their potential to innovate through frugal products to manage the severity of the COVID-19 virus transmission [4].

Frugal science is a concept by which the complexity of product and the associated cost of the product is reduced using simple design strategies such that they can even be made available in resource-limited environments [2]. The term "frugal science" can also be referred to the usage of economical equipment to study and explore the scientific world. Frugal science makes it easy for the researcher/explorer to discover more using limited resources even at very distinct places which are not technologically advanced as compared to the rest of the world. The frugal devices help to make science very handy and reduce the cost to study science. The word "frugal" is also an adjective used for things/products which are economical to use, such products are therefore valued by the consumer for its low cost, sustainability, and quality [5]. On the same lines, frugal innovation refers to "the commercialization of quality products and services that are affordable to the masses". The frugal innovations increase the affordability of the products and make the products synchronized with the economy. From an estimate, 20-25% of the total medical costs are of the devices used in the diagnostics which makes the entire diagnosis highly expensive and unaffordable for most of the population [1]. Besides healthcare, frugal innovations can also play an important role in the field of providing accessible education to all. The equipment used in science education and research such as microscopes, centrifuges, etc are also extremely expensive and not all can afford it. It becomes even more challenging if number of users is more. Another problem being a requirement of a constant power supply to operate such equipment and high maintenance costs which makes it difficult for underdeveloped or economically backward areas to operate and maintain them.

Thus, Frugal products provide alternatives to these expensive and electricity driven devices and make it possible for even the most economically backward areas to use these alternatives and provide sustainable and cheap education and good healthcare facility to all. The frugal science will ensure that the functionality of expensive devices reaches maximum number of people and especially those living in remote conditions [6]. Hence, the main principle of frugal science is to act as a bridge between the medical facilities and their application for the society. These frugal devices are also in line with the concept of sustainable development as they are eco-friendly. As the demand of cost effective and affordable health care and education system is increasing in the low and middle-income group population, the frugal innovations are becoming necessary.

Frugal devices must aim to achieve three main objectives: cost optimization, efficiency, and compact build [12]. There are a number of analytical devices which have been constructed keeping these objectives in mind. Fig. 1 shows important landmarks of frugal innovation in the field of medical science starting from widely used Stethoscope in 1816 used to listen to sounds of animal or humans. The Shaker Scope is one such example, developed at the Morriston Hospital in Swansea, UK to act as a source of light for the ear, eye, and throat examination. The ShakerScope provides power to the light source through the electric current produced by electromagnetic induction [2]. The US Military has used ShakerScope as a laryngoscope in Afghanistan and in the earthquake-hit parts of Haiti [13]. Smartheart is a personal ECG device and allows real time heart monitoring, was developed by SHL Telemedicine [14]. Jaipur foot, a prosthetic limb developed in India with co-operation of the Stanford University, is made up of wood and sponge rubber and is highly light weighted and mobile [2]. 3nethra- was developed as a non-invasive, portable, and low-cost imaging device to screen common eye problems especially useful to rural populations [1]. Another portable and cost-effective technology, Micro PCR, has been developed by Bigtec Labs [1]. A Hand cranked defibrillator is yet another innovation built by Jeevtronics which is battery-less and maintenance free and suitable for rural areas without electricity. Its design and engineering is comparable to international standards. The most important advantage being its cost which is 4 to 15 times less than the comparable devices. The rate of sudden cardiac arrest in India is 3-4 times higher than the developed countries killing about 6-7 lakh people annually due to the cost of conventional defibrillators and lack of stable grid electricity [15].

Another such frugal invention is Mitticool, a refrigerator made from clay, glass and plastic which keeps cool for several hours without electricity [16]. Annie a Self-learning Braille Device from Thinkerbell Labs is the world's first Braille literacy device with which visually impaired people can learn to read, write, and type in Braille independently in a fun way [17].

Some more such recent innovations developed in India have been listed in table 1 [18-25] including a promising low cost, painless, free from radiation, easy to use and portable Breast Cancer screening innovation (Niramai) an detect breast cancer at early stages of development. This can be used by women of all age groups and can be helpful in saving a life of a cancer patient. This is low-cost innovation as compared to the currently used Mammography, which requires expensive equipment and services of an experienced radiographer [26].

Another example of frugal device is Foldscope, an origami-based paper microscope developed by Manu Prakash, *et al*. to popularise science has found various applications including on-site food and beverages sample analysis, school teaching, and preliminary data collection for research projects studies requiring the use of microscope [8]. The same team of scientists has also developed a paperfuge, a low-cost centrifuge at the Stanford University, USA. These are the alternatives to the routinely used devices microscopes and centrifuges. Both the microscope and the centrifuge are required in the educational setting and the medical labs but owing to their high cost these devices become unaffordable to most of the educational institutes and hospital research labs situated in the rural, low-income areas tier 2 and tier 3 cities where electricity poses major issues many times and people cannot afford such expensive devices for diagnosis. Hence these can be popularised and their use can be expanded. The following section discusses in detail these two innovations and their applications in education and healthcare.

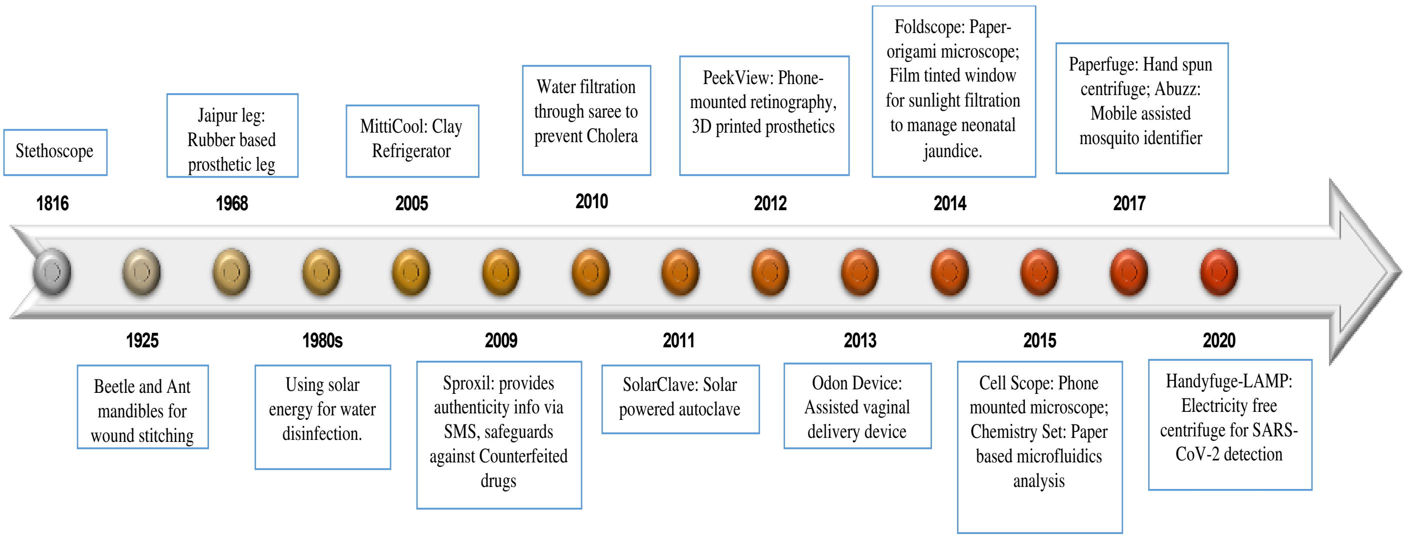


Fig. 1: Landmarks of frugal innovation in medical science [2, 7-11]

Table 1: Recent frugal Innovations in India [18-25]

S. No.	Name of Innovation	Application	Approx Cost of Innovation in USD ($)	Approx Cost of competitive Products available in Market in USD ($)
1	Aum voice prosthesis http://www.innaumation.com	A low-cost speaking device for throat cancer patients who have undergone laryngectomy (surgical removal of the voice box) and lost their voice; Enables them to be able to speak post-surgery. A one size prosthesis fitting most patients, with a biocompatible, disposable, and autoclavable wood inserter enabling surgeons to do the insertions in OPD's, eliminating the need for OTs.	1.0	400- 600
2	Stamurai https://biotech-solutions.com/	A Speech Therapy App for Stammering. This app provides instructional videos for exercise training and practice. The Currently available solutions are expensive and with 80% relapse rates; Less accessibility of such solutions and speech therapists in developing countries like India.	16/year in developing countries; 100/year in developed countries).	5,000
3	Sampark Smart Shala™ https://biotech-solutions.com/	A cutting-edge, frugal solution, to improve learning outcomes based on user-centric design thinking especially in rural areas.	1 per child per annum.	500
4	NiramaiThermalytix https://biotech-	A non-contact, radiation-free, and painless solution for breast health and	1.36/screening	1500-8000

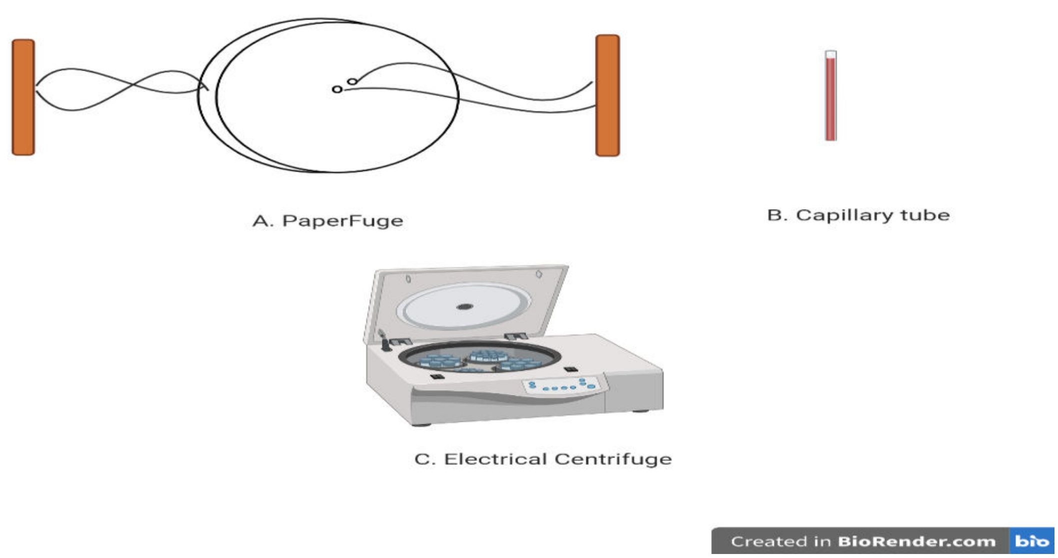
	solutions.com/	cancer screening. A machine learning and AI-based Computer Diagnostic Engine called Thermalytix, interprets thermal images and gives quantitative report for breast health abnormalities. Alternative to the commonly used Mammography, which is painful, requires expensive equipment, personnel for operating and based on X rays, therefore cannot be used for multiple times		
5	Swagene http://swagene.com/	A Molecular diagnostic tool for personalized therapy. It is an affordable solution for infections, cancers, pregnancy, infertility, heart diseases	30-200	10,000 or more.
6	Daksh and Keyar http://www.janitri.in/	KEYAR, a wearable intrapartum Fetal Heart Rate (FHR) and contraction monitoring device provided with reusable/disposable sensor patch for attaching onwomen's belly. It analyzes the pattern and gives alerts if fetus is in distress; Works through mobile application DAKSH through which vital signs of a pregnant woman in labor can be monitored. FHR and uterine contraction are displayed in a secure easily interpretable format understandable by a low skilled health worker in contrast to existing cardiotocography (CTG) with a graphical output requiring a skilled health worker.	500	2700 and more
7	Genomix Malaria Pf/Pv antigen self-detection kit http://genomixbiotech.com/	Qualitative Assay for determination of Malaria Plasmodium falciparum Specific Histidine rich protein - II (Pf HRP-II) and Malaria Plasmodium vivax Specific Lactate dehydrogenase (pLDH) inblood specimens; Performance validation by WHO/FIND/CDC.	0.4	20-21
8	SENSIT COVID-19 IgG/IgM rapid test. http://www.ubio.in/	Detects anti-COVID-19 antibodies in human samples; can be used to detect viral antigens from human blood/ plasma/ serum in a very short time.	2.7	33
9	Dozee https://www.dozee.health/	A contact-free health monitor and personal health companion for heart health, respiration, sleep cycles, stress levels etc with high accuracy; Features include first of kind AI Powered Meditation with Biofeedback for quick relaxation; AI powered Alert System, personalized health solutions and clinically relevant reports	97	338
10	HIV-1 RNA extraction and testing using glucometer. http://www.wobblebase.in/	A Kit designed for isolating Virus RNA from Plasma and Serum samples. The assay involves viral RNA amplification and detection using a glucometer.	0.68/sample for extraction and 5.4 for testing.	4/sample for extraction and 67-94 for testing.

2. PAPERFUGE: FRUGAL ALTERNATIVE TO CENTRIFUGE

A centrifuge is an important instrument for any medical diagnostic and educational facilities for several purposes such as for separating plasma from the whole blood sample, or to carry out estimation of the pathogenic load in a biological sample such as blood, urine, and other body fluids [27]. For the modern diagnostics, centrifugation is a critical step in order to get rid of the unwanted debris present in the sample and thus aids in proper diagnosis of the disease. The centrifuge not only finds its use in the medical field but is also used in research and academic fields for various experiments. The currently used centrifuges have a major disadvantage that these cannot be used in field conditions because of stringent requirement of electricity and being extremely expensive and bulky [28]. Some of the researchers have actually started to use salad- spinners and egg- beaters as an alternative to the centrifuge in field conditions, but these alternatives have limitations in terms of low rotational speed and a large requirement of the mechanical energy to operate restricting its application. These approaches turn inefficient as well while working with samples of small volume [29].

Paperfuge is low cost, portable and human-powered centrifuge which can achieve high centrifugation speed and be used in resource limited environment [29]. It is made up of two card-stock paper disc, braided finishing line is used as strings as these have high tensile strength, the handles are made up of wood/ PVC pipes, the drinking straws are used as a secondary leakage from the capillary, the straws are sealed using epoxy (Fig. 2A-B). This makes paperfuge an extremely low cost (<20 cents/less than 20 INR), lightweight (2 g) and easily portable device on the fields. The design and working of the paperfuge is inspired from the historic whirligig (circular discs spun by pulling on strings passing through their centre) toys. Paperfuge claims to achieve a speed of 125,000 r.p.m. (30,000g) just by human power, and without any electricity. The paperfuge can be constructed from different materials such as paper and plastic. It operates on the principle of successive 'winding' and 'unwinding' phases. In the latter phase, the force of human hand on its handles or strings accelerates the disc to a maximum rotational speed. In the winding phase, the input force comes to zero, the inertia of the circular disc rewinds the strings and brings the hands back inwards. The strings being flexible, wind beyond the geometric zero-twist point, undergoing a number of twisting states. After coming to a tightly packed supercoiled conformation, the disc momentarily stops. At this point, an outward force is re-applied, causing unwinding and winding of the strings, thus repeating the cycle [7].

Thus, the paperfuge is ultra cheap, power-free alternative to conventional electrical centrifuge (Fig. 2C) that has opened ample opportunities for point-of-care diagnostics in low resource settings and for applications in science education and field ecology.



A: Paperfuge construction, B: Capillary tube; samples to be centrifuged using the Paperfuge are loaded in the capillary tube and then sealed from both the sides and fixed in between the peper discs, C: Conventional electric centrifuge

Fig. 2: PaperFuge, A hand-powered centrifuge [7]

2.1. Applications of paperfuge

2.1.1. Separation of plasma from blood

The paperfuge is capable of effectively separating plasma from blood within about 1.5 minutes of its operation. The time of operation has been reported to be comparable with the commercial centrifuge (give reference). Critspin centrifuges the blood sample in 2 minutes, at the operation speed of 16,000 rpm and the cost being $700 [7]. Thus, paperfuge can be effectively used as a cheap and reliable alternative viable option for centrifugation to separate plasma from blood.

2.1.2. Quantitative buffy coat test

The paperfuge can be used in the detection of malaria. The blood from infected person is centrifuged for 15 minutes with the help of paperfuge, this centrifugation leads to the separation of buffy coat/granular part (WBCs and platelets). The capillary used for the centrifugation is pre-coated with acridine orange dye, the dye helped in the identification of the malarial parasite (*Plasmodium falciparum*) via fluorescent microscopy [2, 7]. This methodology can also be applied for the identification of the cause of various haemato-parasitic infections such as African trypanosomiasis and malaria [7].

3. FOLDSCOPE- FRUGAL ALTERNATIVE TO MICROSCOPE

Microscopes are the instruments which is probably the simplest and the first device that the students get acquainted with to explore the range of biological samples or we can say the "fascinating microscopic world". It all started in late 1600s with the imaging of *Spirogyra.* Since then, there have been many improvements and extensive developments in the field of microscopy to enhance their magnification and resolution [30]. Microscopes are used to visualize the structure of a cell and its components, and to trace the biochemicals processes. In clinical microbiology, microscopy is the traditional way to identify the pathogen in a clinical specimen. It is also used to assess the water and food samples for potential microbial contaminant. Although microscope is an extremely useful instrument, it has some limitations. The major problem with microscopes is that they are bulky, expensive and most of them require a source of electricity to operate. This results in a limited to no use in the remote and underdeveloped areas and limited accessibility to students. They do not get enough time to explore and appreciate and satisfy their curiosities for the various organisms and their structures. Also, being heavy and bulky makes it difficult to carry it to such locations. Hence 'Foldscope' can be explored as a viable solution to these problems. Foldscope is a paper-based microscope assembled by using the art of origami. It was developed by Dr. Manu Prakash and Jim Cybulski using paper, micro-optics, and magnets. The use of low-cost material results in a product of about US$1. Being made up of paper makes Foldscope light weight and portable. Along with this it provides a fine resolution and a magnification of about 140x when attached to a mobile phone, for taking photos and videos which increases its scope for virtual microscopy [8].

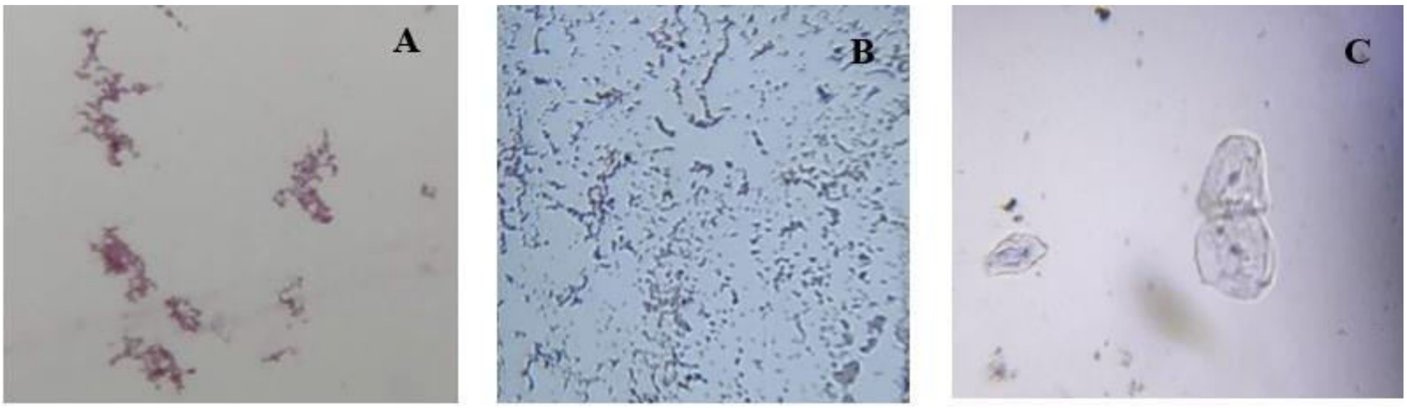
One can use Foldscope to visualize diversity of cells such as bacterial, algal, fungi, plant cells and animal cells. All this makes it an excellent exploratory and an educational tool for carrying out research in remote and under-developed areas. In a recent article, Karabi *et al* recommended that Foldscope could be incorporated in curriculum of every school for better understanding of the subject and to overcome barriers of unavailability of facilities [31]. Science knowledge through exploratory exercises can generate interest in every student. Foldscope can simultaneously also be used to generate awareness about general hygiene and common diseases like dental disorders in school children [32]. The limitation of equipment and space crunch can be overcome by such portable instruments. Like a normal microscope, Foldscope can be used for analyzing clinical and environmental samples also [8].

3.1. Applications of foldscope

3.1.1. Detecting Water Purity

Clean water is the right of every individual. From various sources water is supplied to the households. These sources, however, are prone to contamination by pathogenic microbial population. Majority of these pathogenic microbes are faecal coliforms, which causes several GI tract infections in the humans. "Coliforms are non-sporulating, anaerobic, gram-negative rods. They are thermo-tolerant and reside in the human intestine where they produce lactic acid and CO_2 by fermenting lactose." *E.coli* bacteria serves as an indicator organism for faecal contaminant in the water [33]. The presence of pathogenic species like *Vibrio cholerae, Shigella, Salmonella, Entamoeba histolytica* and several enteric viruses are the potential threats of the contaminated water. As a result, analysis of water for portability is very important [34]. In urban areas, analysis of water is easy because laboratory facilities are generally available.

Unfortunately, the case is not the same in the rural, tribal, or remote areas. The lack of clean drinking water is also a serious concern in those areas. Microscopic analysis through Foldscope is a way to assess the microbial contaminants present in water. Using the simple technique of Gram staining, the presence of faecal coliforms can be determined. Since coliforms are Gram-negative rods, they will appear as pink colour rods in the Foldscope after Gram staining (Fig. 3: A, B). Thus, the water can be analyzed for the presence pathogenic bacterial species using Foldscope.



A: Gram negative bacterial cells, B: Gram Positive bacterial cells, C: Cheek Cells

Fig. 3: Viewing cells under foldscope

3.1.2. Diagnosis of cervical cancer

In the presence of risk factors, there is a growth and expansion of *Human Papilloma Virus* (HPV) in the endothelial layer of endocervix which can induce cervical cancer. Cervical cancer is most prevalent in females of 30-50 years of age. Its early detection is important but in the tribal or remote areas it is quite hard to get a proper diagnosis. Early detection through microscopy can prevent disease manifestation. A cervical cell with cancer will have a huge nucleus as compared to the normal cell. A pap smear when observed under a Foldscope can be used to identify cervical abnormalities [35].

3.1.3. Pre-cancerous Changes in Buccal Epithelial Cells

Prolonged exposure to carcinogens like tobacco etc. can cause breaks in the DNA which leads to the formation of micronuclei. The presence of these micronuclei in the cell indicates the onset of oral cancer. Since there is a time period between the manifestation on cancer and micronuclei formation, therefore detection of micronuclei in cheek cells can serve as an early diagnostic method for oral cancer using the method of Feulgen staining. The cheek cells can beeasily visualized using a Foldscope (Fig. 3C). After Feulgen staining, micronuclei appear as small nuclear body near the nucleus in these cells [36].

3.1.4. Differential Leukocyte Count (DLC)

It is test used to determine the percentage of different types of WBCs in the blood. DLC is used to check the proper functioning of the immune system or to detect an infection. WBCs can be counted using a Foldscope by using standard Romanowsky staining procedure. After counting the respective percentage of each WBC can be calculated to deduce a conclusion [36].

3.1.5. Blood Borne Pathogen Detection

Millions of cases of Malaria are observed every year. A modification in the Foldscope called Malaria scope is being investigated to detect malarial parasite *Plasmodium*. Similarly, using Foldscope pathogens for other blood-borne diseases like sleeping-sickness, schistosomiasis can be detected in a less expensive manner in remote locations [37].

4. CONCLUSION

There are about 4 billion people around the globe which are in low income group with unmet needs even in basic facilities. With the emergence and popularisation of frugal devices, education and healthcare can be made available to this resource-limited section of our society. These have provided the solutions for the real-life problems which the conventional methods were not able to solve [1]. This is partly due to the emergence of new possibilities and developments in device design and research using 3D printing and the art of origami in geometry. Cost of services and remoteness of the area has been an ultimate barrier for providing quality health. There have always been challenges in establishing an environment of science and technology in rural and socially backward areas. Also, the dilemma for acceptance of the new devices is always there. As mentioned by the PaperFuge developers, people had doubts about their device but only after the demonstrations they gained the trust of the people for using PaperFuge in place of the bulky conventional devices [7].

This is an era which revolves around technology and demands a constant advancement in the technology which is being used. To keep the pace with these demands non-conventional, alternative approaches find their way in to develop compact, economical, efficient, and easily accessible technologies. Frugal science aims to develop affordable devices which provide sustainable services from low-cost easily available materials for the needful. Examples of such potential frugal devices are Foldscope and Paperfuge. An easy and safe disposal of these devices makes them a suitable choice while working with an infectious disease. Being extremely light and hand-held devices both PaperFuge and Foldscope can be efficiently used in remote and rural areas. Application of PaperFuge and Foldscope is not only limited to diagnostics, but they can also serve as a tool to teach the concepts of science to the masses, a tool to teach people about hygiene, to create personal healthcare awareness. A way to imbibe the practices which improve their health and help them to maintain a healthy life. To attract the interest of the young minds to learn new concepts and techniques and to develop an innovative thinking routine workshops and demonstrations must be conducted. Such arrangements will not only educate the young minds, but it will also sow the seeds for scientific thinking. Therefore, these devices which will break the barrier of cost limitation and space requirements should be brought to forefront of scientific research acting as the inspirational models for further innovations.

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Conflict of interest

None declared

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