Virtual and remote laboratories augment self learning and interactions: Development, deployment and assessments with direct and online feedback

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Background. Over the last few decades, in developing nations including India, there have been rapid developments in information and communication technologies with progress towards sustainable development goals facilitating universal access to education. With the aim of augmenting laboratory skill training, India's Ministry of Human Resource Development (MHRD)'s National Mission on Education through Information and Communication Technology (NME-ICT), launched Virtual laboratories project, enabling professors and institutions to deliver interactive animations, mathematical simulators and remotely-controlled equipment for online experiments in biosciences and engineering courses. Towards that mission of improving teaching and learning quality and with a focus on improving access to users in geographically remote and economically constrained institutes in India, we developed and deployed over 30 web-based laboratories consisting of over 360 computer-based online experiments. This paper focuses on the design, development, deployment of virtual laboratories and assesses the role of online experiments in providing self-learning and novel pedagogical practices for user communities.

Methods. As part of deployment, we evaluated the role virtual laboratories in facilitating self-organized learning and usage perception as a teaching tool in a blended education system. Direct feedback data was collected through organized workshops from 386 university-level students, 192 final year higher secondary school (pre-university) students and 234 college professors from various places across India. We also included online feedback from 2012-2018 to interpret usage analysis and adaptability of virtual and remote labs by online users.

Results. More than 80% of students who used virtual laboratories scored higher in examinations compared to a control group. With 386 students, 80% suggested adapted to self-learning using virtual laboratories. 82% of university teachers who employ virtual laboratories indicated using them to complement teaching material and reduce teaching time. Increase in online usage and feedback suggests novel trends in incorporating online platforms as pedagogical tools.

Discussion. Feedback indicated virtual laboratories altered and enhanced student's autonomous learning abilities and improved interaction in blended classrooms. Pedagogical analysis suggests the use of ICT-enabled virtual laboratories as a self-organized distance education learning platform for university and pre-university students from economically challenged or time-restrained environments. Online usage statistics indicated steady increase of new users on this online repository suggesting global acceptance of virtual laboratories as a complementing laboratory skill-training online repository.

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Virtual and Remote Laboratories Augment Self Learning and Interactions: Development, Deployment and Assessments with Direct and Online Feedback

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1. Introduction

Trends in Information and Communication Technologies (ICT) have transformed schooling and teaching by bringing in digital contexts (White, 2008). ICTs have a prominent role in improving quality of teaching and learning (Fathima, 2013) and in changing the global status of classroom education (Sasidharakurup et al., 2015). Effective learning has been reported with learners actively participating in the educational system (Yusuf, 2005). Studies indicate students have strong motivation to learn easily perceivable components (Sugerman D. A., Doherty K. L., Garvey D. E., 2000). Approaches for engaging students in curricula include inquiry-based learning, problem-based learning, project-based learning, case-study based teaching, discovery learning, and just-in-time teaching, designed to increase the self-organization abilities of students (Habók and Nagy, 2016). In school and university education, self-organization refers to a student-centered learning approach, where participants have shown to have higher engagement in their active learning process (Froyd and Simpson, 2008). In addition to augmenting students' study skills (Mitra and Dangwal, 2010), it has been suggested that students adopting self-organized or autonomous learning were more satisfied in their work, which may led to success in their education process (Tüysüz, 2010).

Self-organized learning (S-o-L) based on Kelly's (Pintrich, 2004) personal construct theory (PCT) had suggested learning process happened through construction and reconstruction of meaningful reflective experiences (Castelli, 2011). In several institutions of higher education, learning process was managed mainly by teachers or with roles by the society (Ali et al., 2013). Enrolment in education was not governed by government education policies but by household decisions (Florian, 2008). Challenges to retain young learners in science and engineering disciplines included the need for rapid diffusion of secondary education and yearly increase in enrolment of students. Consequently, students have reported not getting sufficient access to classroom and laboratory facilities to practice an experimental research in a better way (Nair et al., 2012). Also, teachers were coerced onto a show-and-tell approach towards teaching (Dangwal, R., & Thounaojam, 2011) where students may not have a role for active participation in improving their own abilities in learning. UNESCO's education report 2014 (UNESCO, 2014) indicated poor access to education and lack of sufficiently well-trained teachers as reasons in developing countries for illiteracy. In some cases, classroom lectures were changing from face-to-face interactions towards innovative modes of including ICT-enabled self-organizing modes (Diwakar et al., 2016) (Istenic Starcic and Bagon, 2014) helping to overcome problems (Chu, 1999) such as time management, lack of sufficient laboratory materials and equipment, and training trial issues (Swan, 2003). Use of such ICT enabled visual information has shown to facilitate cognitive learning and improves memory retention (El-Sabagh, 2010). It also helps to strengthen student motivation and improves the active learning process in a better way (Narciss et al., 2007). Studies also reported the importance of including this pedagogical method in educating a group of students with minimum or no involvement of an instructor (Mitra et al., 2005). Analysis of student feedback post virtual laboratories suggested that explicit user interactions in virtual laboratories aid teaching and learning experience (Radhamani et al., 2014). Studies have also suggested improved academic performance in students using virtual laboratories in their curriculum (Radhamani et al., 2014). Case studies on virtual laboratories encompassing student and teacher groups from different Indian universities via workshops and online feedback are listed elsewhere (Diwakar et al., 2014).

In the last few decades, software-based virtual laboratories in different fields have been developed by various institutes for fulfilling the educational objectives of a conventional classroom education. Library of Labs (LiLA) project (http://www.lila-project.org/) by University of Stuttgart has been developed to provide access to virtual and remote labs with a tutoring system and 3D environment for online education. Go-Lab Project (Global Online Science Labs for Inquiry Learning at School), a European collaborative project (http://www.go-lab-project.eu/) focused on implementing online virtual and remote experimentations in science laboratories for the large-scale use in school education. Virtual Community Collaborating Space for Science Education (VccSSe) project (http://www.vccsse.ssai.valahia.ro/), which is a joint collaboration between several institutions, provided training on using virtual instruments for teachers and students in the field of chemistry, physics and biology. MIT iLabs (https://icampus.mit.edu/projects/ilabs/) provided online access to remote labs for distant users for experiencing a hands-on lab session over internet. BIOTECH Project'(http://biotech.bio5.org/home), developed by University of Arizona assisted teachers in providing classroom activities related to molecular genetics for student communities. VITAL Lab (http://vital.cs.ohiou.edu/), Lab Share from Australia (http://en.wikipedia.org/wiki/Labshare), NASA's virtual laboratory and HHMI Virtual laboratories (http://www.hhmi.org/biointeractive/vlabs), are some other examples of web-based interactive education platforms that provide the students with skills and techniques. Most of them were specified for education purposes, but due to technical complexity generalization to an online platform needs further advancements (Potkonjak et al., 2016).

This paper explains the design and implementation of virtual and remote laboratories based on an Indian laboratory setting. The objective was to deploy the online laboratories with multiple groups of students from university and pre-university levels and to test for self-organized learning and perceived usage by university professors. The study intended to understand learner adaptability in using virtual laboratories and assessing its role in complementing classroom education and as a new pedagogy for distance education and for enabling access of equipment and educational content free of cost.

2. Methods

All the virtual laboratories are freely available at http://vlab.amrita.edu. The development and deployment of these ICT-based tools are detailed in this section.

2.1 Infrastructure of Virtual and Remote Laboratories

Software and hardware development phases of creating online labs were discussed in the following sections.

2.1.1 Development and Conceptualization of Animation Based Labs

Towards the development of animation based virtual laboratories, the initial process included transforming an experimental protocol “real world” scenario into an “abstract world” via a sketched experiment storyboard. A storyboard of the experiment helped finalizing the development phase of animation process. In order to minimize possible errors while virtualization, critical steps in biotechnology experiments such as handling of pipette, discarding biohazard materials, working with laboratory equipment and personal care were sketched. The prior steps in the experiments such as preparation of chemicals, reagents, and stains were eliminated to manage time related issues. The preparatory steps were included in theory and procedure sections of the experiments. Expertise in particular arena test and evaluate interim versions of the storyboard. Next step was to develop a “model world” by integrating the procedural practices with click gestures and visualization techniques to provide an actual feel of laboratory. It included a process that needed coordination of engineering techniques for conceptualization of biological phenomena in order to provide an interactive environment to users. Visual scene animation of experimental set up was programmed using multimedia and mark-up languages. Simple controls such as pause, stop and replay were included to facilitate users focus on different aspects and viewing options. The prototype of the animated lab were implemented in graphical user interface and tested in multiple browsers and platforms. It was then tested among limited sample size of target population; teachers and students. After fixing the initial testing, the final version was uploaded for online usage.

The animation-based labs were classified into two groups: Perceivable labs and Emulation labs. Perceivable labs are animation only labs which are visualization oriented, were users could understand the experimental concepts with pictorial representations of laboratory scenes in the computer screen. One example of perceivable labs is Gram Stain Technique in Microbiology lab, a differential staining technique used to classify and categorize bacteria into gram positive and gram-negative organisms. Emulation-based labs included pictorial representations of the lab with user interactions at critical points, such as fine and coarse adjustments of microscope in cell biology and brain slicing protocols in neurophysiology labs. When a user performed the experiment off sequence, error messages were displayed as pop-ups. A classical example of emulation-based labs is blood grouping experiment in immunology lab, where the interaction was designed to include reagent mixing steps, biohazard discarding point and result analysis focussing the engagement of the user in the experimental process.

2.1.2 Organization and Design of Simulation Based Labs

A synergy between biology and mathematics has been intertwined to model interactive simulation-based labs, providing an idea of what to perform in a real lab. Simulations included mathematical reconstructions of real-life datasets and biophysical approximations facilitating user interactions.

The focus of the simulation-based labs was to reduce the cost of experimental set-up and effort in teaching basic laboratory protocols in electrophysiology such as patch clamp, current clamp and voltage clamp at the university level. Neuronal biophysics simulations using Hodgkin-Huxley (HH) mathematical model were used to illustrate ionic mechanisms underlying the initiation and propagation of action potentials and their propagation (Hodgkin and Huxley, 1952). HH models include a set of nonlinear ordinary differential equations which approximates the electrical characteristics of excitable cells such as neurons and cardiac myocytes. The time derivative of the potential across the membrane V_m is proportional to the sum of the currents in the circuit. This is represented as follows:

$$\dot{V}_m = -\frac{1}{C_m}\left(\sum_i I_i\right),$$

where, the lipid bilayer is represented as a capacitance (C_m), and I_i denotes the individual ionic currents of the model.

Mathematical models were validated via alternative implementations in platforms like MATLAB, Java, and Python. All simulations were implemented using Javascript or Action Script. This implementational strategy was meant to reduce the load at the server end, relatively efficient and higher execution speed. While using the simulator, a copy of simulator of a few kilobytes in size was needed for users to execute the online experiment. Export feature was also included to facilitate the user to download simulated values as a Comma Separated Value (.CSV) file for future and extended usage.

The simulation-based labs were classified into two groups; Predictive modelling-based labs and Quantification-based labs. A classic example for predictive modelling (Dickey, 2012) based labs is population ecology lab, which focused on understanding how population dynamics changes over time. In predictive models, parameters were modelled to reconstruct the dynamics affecting the rate of growth of a population. To predict population dynamics, variables such as number of individuals in the population at each time, change in number of individuals over time, initial population size and population growth rate were allowed to be varied. Using this model, tiger population in India till 2012 was predicted by students in a previous study (Parasuram et al., 2011). Other modelled simulations incorporated mathematical models for user perceived educational precepts in population ecology.

In quantification-oriented labs, parameters could be varied on a set of processes included in the experimental model(Mendes and Kell, 1996). In biochemistry, design of experiments was centred around parameters that modelled changes included varying values for volume of reagents, concentration of reactants/reagents, adjusting the running speed of drops (0.5N HCl) from burette, and selecting appropriate indicators for performing experiments, to understand its effect in a chemical process. In microbiology experiments, student learners were allowed to change the dilution factor, vary dilutions of virus sample and plaque count to study Plaque Forming Unit (PFU). In our molecular biology experiments, such as agarose gel electrophoresis, varying parameters such as concentration (%) of agarose, type of DNA, marker size, and varying restriction enzymes to separate the DNA fragments based on their molecular weight were employed to include teaching content alongside process information. Simulations for experiments, where results could not be accurately determined from physical experimentations were also modelled.

2.1.3 Architecture of Remote Labs

There are several documented cases in literature involving the implementation of remote labs in engineering education. Stevens Institute of Technology (SIT, USA)'s remotely accessible experiment set-up included a Linux-enabled web server to connect lab-set-up to outside world, the Graphical User Interface (GUI), was developed using conventional HTML pages, Java applets and CGI/Perl scripts(Esche and Chassapis, 2003) University of Technology, Sydney (UTS) also developed remote labs with a goal to ensure greatest flexibility of access to different users. Arbitrator software was used to authenticate user requests. In the revised architecture, Virtual Network Computing, an open source software was used to support additional features such as control sharing during experimentations(Lowe et al., 2009). MIT iLabs also developed distributed architecture (Web service architecture) for remote labs as an addition to their existing laboratory system, where the equipment is managed by lab servers, authentication and access is moderated by a service broker (Harward et al., 2008).

Initial Implementation Phase

A remote lab in neurophysiology was piloted, where neurons were modelled, for studying action potentials and bursting phenomena using analogue circuit equivalent (Parangan et al., 2010). For investigating membrane potential properties and basic ion channel properties of granule cells on hardware platform, an analogue model was adapted from Maeda and Makino model. Proprietary software was used to analyse inputs and outputs of experiment. Later remote labs were included in physical sciences, biological sciences, mechanical engineering and computer science (Freeman et al., 2012; Kumar et al., 2014, 2016). As a prior step in building remote labs, lists of experiments that were pertaining to biotechnology and engineering courses were selected. Since controlling entire input parameters was impractical, a section of usable input space was mapped to the controls. Remotely controlled equipment or laboratory set up was first connected to a commercial Data Acquisition (DAQ) device, which interfaced the lab server with the equipment. DAQ functions to receive and send signals between the remote equipment and server. Entire experimental set up were connected to the lab server. Server received the requests from remote users over the internet, which sent device command to the equipment hardware through DAQ. The control signal or the input from the user to the equipment was transferred to the device as a set of parameters via an XML file. The communication between the server and the remote user was made possible with the help of service broker. Server notifies experimental output to remote users via service broker. The experiments under remote labs were designed to provide remote access to a single user at a time. Initial version of the graphical user interface was designed using Action Script and modelled to run on browsers with flash plug-in. Input was processed as GET or POST parameters to the web services installed in the lab server. For providing an overview of equipment usage and operation of a physical laboratory, live video streaming the lab set-ups were also included via an ordinary web camera. Usage logs from client side was handled with an apache server. A slot-booking system (scheduling system) was employed to reserve practice-directed time slots to avoid multiple user conflicts. Control parameters were also provided depending on implementation convenience and feasible usage from remote locations. For example, in light microscopy experiment, controls are provided for fine and coarse adjustments of microscope. Specimen was fixed to the microscopic slide and the user could move the microscopic lens over the specimen by moving virtual slider in the interface (**Figure 1**).

Open Hardware Model – A FOSS Approach

The labs were re-implemented as a Free and Open Source Software (FOSS) implementation using Java-based webserver for communication purposes and Raspberry Pi devices as controllers. When a remote user accessed an experiment, a http-GET request was sent through the backend of the UI to the lab server. The request was then handled by Java webserver and gave command to the Raspberry Pi device and the experiment was triggered. Experiment output was sent via an http-RESPONSE to the user interface as xml, JSON etc.

Proprietary versus Open Source Implementation

Since the commercial DAQ device was expensive, several experiments were deployed in a single DAQ. Data interference from multiple channels were reported as a major concern in this implementation process. In FOSS implementation (Raspberry Pi 2 with an ARMl176JZF-S 700 MHz processor, an Ethernet port, 2 USB ports and 512Mb RAM), general purpose input/output pins of the device supported automated data acquisition. Also, a single raspberry device supported up to four experiments, reducing the deployment cost. Hardware cost and network device cost were also comparatively low (Vijayan et al., 2017). Wi-Fi adapter on Raspberry Pi made it portable when compared to other data acquisition cards. Specific java codes are a requisite for each implementation.

We have developed 30+ online labs and enabled over 360+ online experiments in physics, chemistry, biological sciences, computer science, and mechanical engineering disciplines (see supplementary material) and are hosted freely. Registration of users was implemented to enable track usage statistics. The experiments were deployed in Collaborative Accessibility Platform for Virtual laboratories (CAPVL) (Raman et al., 2011) and accessed free-of-cost by learners from different locations.

CAPVL framework was designed with a Collaborative content management system and a virtual lab management system. Content Management in CAPVL included subject of choice, topic and experiment. The content included theory, procedure, animation, simulation, remote trigger, self-evaluation, assignment, and references. Module management and course management allowed syllabus mapping of laboratory modules with various university syllabus and deploying and managing the contents for remote usage. The version controller records the changes that has been made to a file over time which enables to recollect specific versions later. Template engines helped in development of logic and presentation in an easier way for improving the flexibility for modifications and maintenance of the contents. Other than this, virtual laboratories repository records the basic information (metadata) about particular experiment access. For a statistical overview, usage logs were recorded. The virtual laboratories management system was incorporated with a Kerberos-based single sign-on system. The user-management system improves the reliability and flexibility without compromising security issues. Feedback portal allowed the developers to collect specific feedback from all learners and instructors using the labs (**Figure 2A**).

After successful authentication, input from the user to the experiment or equipment was transferred as digital signals or parameters. Allowed range of input parameters and signals were fixed in the initial stage. User input was processed and the data was sent to main server, triggers the experiment and the generated output was send back to the user (**Figure 2B**).

3. Deployment of virtual and remote laboratories via Field Trials - Evaluation of Pedagogical Effectiveness

As a part of testing the online platform amongst different users, field trials (workshops) were carried out at different education institutes for students and teachers (**Table 1**) in rural and urban areas within India. For the data reported as part of this paper, many student and teacher workshops were conducted, involving several institutes in South India. The focus of the workshops was to provide a comprehensive overview of the role of virtual and remote labs in supporting their learning style or education system. Online feedbacks were also evaluated to understand learning outcome and flexibility of user-interactions. (Sample subsets are included as supplementary material).

3.1 Workshop based case studies on Biotechnology virtual laboratories

Several tests were carried out with varying numbers of users (students and professors) and our test cases are reported.

3.1.1 Perceiving User Behavior and Analyzing User's Role in Autonomous Learning via Virtual laboratories

This study was carried out with 192 university students (undergraduate and postgraduate) via face-to-face workshops organized at different places in India. Also, virtual laboratories were presented to 192 school students of final year higher secondary grade (the year before they join University), during an inter-school event conducted as a part of an interschool's exhibition in Kollam (India) in 2014. Both learner groups were asked to perform any of the Biotechnology experiments (choosing one that was not familiar to them). Student groups followed the common instructions provided on the virtual laboratories website for completing the laboratory exercise. Test groups were made to go through the theory, procedure and self-evaluation components sequentially before experiencing the simulator or animation or remote panel parts of the virtual experiment. With the feedback provided, the parameters related to online learning including Usability (US), Self-organization (SO), Learning Engagement (LE), Memory retention (MR) and overall advantage of the virtual system were analysed using Cronbach alpha scores. Cronbach alpha measured both reliability and internal consistency of the parameters under test (Bocconi et al., 2012). US referred to the adaptability of ICT techniques in education for enhancing user's learning ability. SO referred to the usage of virtual laboratories by students in their learning process in the absence of an instructor. LE indicated whether virtual labs be an interactive platform for student's constructivist learning, a factor that describes student-student interaction. MR indicated whether virtual laboratories help students to recollect their concepts on experiment without a real laboratory environment (Peyman et al., 2014)(Diwakar et al., 2016b). For analysis, feedback questions (questionnaire-based) were prepared on the basis of TAM and Open Educational Resources (OER) model (Raman et al., 2014) (**Table 2**). Users rated the questions by giving Likert-scale numerical values from 1 to 5 (1- Very poor, 2- Poor, 3- Average, 4- Good, 5- Excellent) for TAM based questions and for a choice of agree and disagree for the OER questions. Cronbach alpha was used for internal consistency check within evaluation and assessment questions and their responses (Cronbach, 1951).

3.1.2 Pre-test and Post-test Evaluations

As a consequent step to identify the role of virtual laboratories as a self-organized learning platform, a typical pre-test/post-test evaluation as a criterion was used in this study. The study group, 384 (same set of student groups as in the previous study) students were divided into two groups; Control Group and Test Group. Control group comprised of 192 students (96 university students and 96 pre-university level students) and were subjected to traditional classroom-based learning of gram staining experiment in virtual microbiology lab. The overall time period for the study was limited to 1 hour. Test group comprising of 192 students (96 university students and 96 pre-university level students) were subjected to virtual laboratory-based learning of the same experiment without the help of an instructor. The time period of the study was limited to 20 minutes. After completing the experiment, both groups were subjected to a pre-test, with a set of question based on the experimental concepts and observations. Performance of students in the examination was recorded. The students in the control group were then subjected to virtual lab-based learning and a post-test was conducted to them with a set of questions, that included similar questions as in the pre-test. Some observation-related questions (such as colour of primary stain, secondary stain, and microscopic observations) were also included in post-test in addition to pre-test questions. The scores were then tabulated for analysis.

3.1.3 Analyzing the Role of Virtual laboratories as a Flexible Teaching Platform

Both qualitative and quantitative analysis of content quality, design of the syllabi, easiness of the material, extended use of technologies in improving quality of education, were carried amongst the teacher groups. The survey was done via a feedback session with 91 university teachers and the questions were based on how the teachers can effectively utilize this online tool in their daily teaching process. Teachers' feedback was evaluated for validating our previous results (study carried out in 2014 with 50 university teachers) (Diwakar et al., 2016b).

1. Do you think virtual laboratories could be used as a substitute for class room presentations in the classroom teaching?
2. Virtual laboratories provide new inventions towards effective educational supplementing the regular class room teaching. Would you agree?
3. Virtual lab demonstrations are effective in an overcrowded classroom scenario. Would you agree?
4. Do you think virtual laboratories can be used as a laboratory material?
5. Virtual laboratories can be used as an examination component to assess user performance in a better way. Would you agree?

3.2 Usage Analysis of Biotechnology Virtual laboratories – A Case Study with CAPVL Online Portal

The CAPVL employs usage roles such as administrators to moderate and track usage of the deployed virtual laboratories. Administrator role allows to create new experiments, checking the online feedback provided for each experiment, analysing actual access time and period of users performing the experiment, monitoring quiz reports of user community and tracking of bugs reported by virtual laboratory users. As a part of analysing the usage of virtual laboratories from distant locations, online feedback from different users were evaluated. The feedback questions were categorized into two sections; Technical feedback focused on questions relating to user-friendly approach of virtual lab system (Adaptability) and User experience feedback focused on questions relating on the usage of virtual laboratories as learning or teaching platform (Perceived usefulness). Feedback survey has a rating on Likert-scale as (1-Poor, 2- Average, 3- Good, 4- Very Good, 5- Excellent). The feedback survey included the questions (**Table 3**).

3.3. Workshop Based Case Studies on Remote Labs

3.3.1. Analysis of Remote Labs as Supplementary Laboratory Tool in Real Lab Environment

To analyse the role of remote labs as a tool for reducing difficulties faced in a traditional classroom, a pilot study was conducted amongst 194 undergraduate bioscience students. Study also included 93 University professors handling biology courses to analyse how the remote labs can aid in reducing their workload in a traditional classroom. During data collection, participants were asked to perform any of the biotechnology remote lab experiment from a list of 20 remote experiments. The scheduler allowed users to access remote experiments concurrently. A set of questionnaire-based online feedback (TAM model) was collected to analyse user's adaptability of remote labs in curriculum and to analyse the effectiveness of using remote labs in teaching.

3.3.2. Analysis of Biotechnology Remote Labs as a Distant Education Tool – A Case Study Based on Online Feedback

For this study, we evaluated online feedback received for 20 remote triggered experiments and selected 2500 feedback responses to have complete and validated data points for analysis. Other feedback was not included to prevent sparseness in responses. Users indicated their responses by marking yes or no to a set of questions (**Table 4**).

4. Results

4.1 Students Adapt to Self- Learning with Virtual Laboratory Usage

Usage feedback data suggested 82% users were able to use and adapted to self-organised learning through an ICT environment. 18% of users faced usage issues that evolved from lack of computer provisions (data not shown).

73.81% students indicated usage of ICT tools helped them in engaging learning (LE) by improving student -student interaction in a classroom. 74.93% students indicated virtual lab usage supported their education in an anytime-anywhere scenario without a physical presence of an instructor and they agreed post virtual lab usage helped them to perform better in real lab. 79.93% students supported virtual laboratories helped them to promote their self-organized or student-centred learning (SO). 74.28% of students suggested ICT enabled virtual laboratories as an Interactive learning platform and a supplementary classroom material for their learning (US) (**Figure 3**). Since only those with Cronbach alpha value greater than 0.80 were included, feedback questions demonstrated internal consistency (**Table 5**).

Pre-test and post-test examination scores of control group and test groups (**Table 6**) were analysed. 82% of university level students and 77% of pre-university level students were able to score in the range of 70-79% marks in the post-test, improving the class average from the pre-test scenario. The same users did not score as much in their pre-test evaluations. Also, 82% of university level students and 81% of pre-university level students in test group scored in the range of 70-79% marks after using virtual laboratories as a learning exercise.

4.2 Blended Learning Models as a Key to Enhance Laboratory Education

The usage of virtual laboratories by university or college teachers teaching biotechnology courses was analysed. 85% of teachers indicated usage of computers as usable in their day to day life, 82% teachers indicated use of virtual laboratories as a substitute for their classroom presentations, 83% suggested usage of virtual laboratories as an examination component to assess student's performance, 82% of them suggested virtual lab usage reduces their time spend in preparing materials for students and 84% teachers indicated virtual laboratories as new pedagogical practices towards better education supplementing their classroom teaching. Cronbach's alpha value (significant >= 0.80) was used as criteria for feedback questions related to usability (**Table 7**).

Teachers appreciated virtual laboratories post training session and some comments by the teachers are listed:

1. "If there are two batches of students to do experiments in the wet lab, we have to explain the experiments twice. Sometimes we miss certain important points (of the scientific content) during our lecture. But virtual lab reduces that work load and makes it easier for both teachers and students".
2. "This is an "innovative teaching" method; instead of teaching several hours, writing on black-board, writing down the class notes – it is very interesting to have animations in the education system".
3. "At the school level, most of the students are unable to do all the experiments properly due to lack of equipment or other facilities. So it would be very useful for students if we include experiments according to school syllabus also". "It is innovative and we can learn a lot more than regular theory classes".

Comparing responses of teacher's in the year 2014 and 2015 (**Table 8**), Pearson correlation coefficient was estimated as 0.9020, a strong positive correlation, which implied that high X variable scores (teacher's positive response in the year 2014) correlated with high Y variable scores (teacher's positive response in the year 2015) and vice versa. Estimated p-value was 0.036171 and was significant ($p < 0.05$).

4.3 Online Usage Trends of Virtual Lab Experiments

The virtual lab online portal had collected more than 300,000 feedback received till January 31, 2018. In order to extract useful information without concerns of sparseness and unsolicited data, we processed the feedback of 10 most popular experiments, in the virtual lab website. From 49842 feedback responses, 49800 valid feedbacks were evaluated (other feedback eliminated due to incomplete data) for testing the virtual lab adaptability and its usage in the curriculum of university education in science and engineering disciplines all over the world. The percentage wise rating given by users for technical feedback and user experience feedback were tabulated. 58% (28884) of users rated virtual laboratories as an excellent tool for ease of use, 20% (9960) of users rated it as very good, and 18% (8964) indicated as it as a good platform for laboratory education. Fewer percentages of users found it difficult to work with the virtual lab experiment and thus they rated the technical support of virtual laboratories as average (2%, 996) or poor (2%, 996). Further analysis has shown that students faced issues while working with virtual lab experiments. Statistics showed that 62% (30876) users supported the use of virtual laboratories as an excellent complementing tool for classroom education, 15% (7470) rated as very good, and 10 % (4980) each suggested it as a good or an average tool after performing the virtual laboratories experiments. Fewer percentage of users (3%, 1494), rated it as a poor online material.

Related study on online statistics extracted from CAPVL indicated that virtual lab users have grown rapidly on an yearly basis (also see supplementary material). In the year 2012, when the virtual laboratories were publicly launched, number of registrations was 14596 whereas the current number of users is 305327 (February 27, 2018).

4.4 Users Prefer Remote Labs as Supplementary Education tool

During workshops, 90% of participants selected remote light microscopy experiment as a learning exercise. Participants (teachers and students) operated microscopic slides with a plant cell and an animal cell (specimens) that were fixed on the stage of the microscopes and they finished experiments remotely. Verbal and direct feedback analysis indicated user's choice of remote labs as a learning platform.

From participant's feedback, 60% of them suggested that remote labs were useful supplementary tools for making the biotechnology education more interesting and easier. 25% rated it as a good online material for effective understanding of the concepts. Nearly 15% of the participants rated this as either average material (**Figure 4A**). Lower rating was also correlated to network connectivity issues faced by the participants (data not shown).

4.5 Blending Remote Labs in Laboratory Education Helps University Teachers

Among teachers who participated in the remote lab workshop, 84% suggested that advanced technologies like remote controlling of lab equipment were helpful in their classroom scenario, whereas 16% did not favour use of such tools in blended learning. A participating college teacher commented: "Although the remote lab didn't feel as real as the actual lab, remote labs allows student (to) practice the experiment many times and compare the results in order to have a better idea. This reduces our efforts in teaching the experimental concepts in the classroom so many times".

4.6 Remote Labs as a Distant Education Tool

From the feedback data collected from online users, 80% users suggested that the overall interactions included in remote labs are satisfactory to understand equipment control or experiment usage. 75% users indicated that the topics covered under the remote labs were relevant to the syllabus at their institute. 25 % users suggested including more experiments on Bio-inspired robotics and biophysics lab to relate to their syllabus with inclusion of remote labs. 78% users indicated their choice of blending remote labs in their laboratory education. 90 % users suggested that remote labs reproduce valid data realistically as in the case of traditional lab. 94% users indicated that content provided by remote experimentations was easily understandable even for distant learners, thus augmenting remote lab as a distant education tool for enhancing biotechnology laboratory education (**Figure 4B**) (**Table 4** for feedback questions).

5. Discussion

In the context of sustainable development of educational technology, this paper covers the design, development, deployment and usage testing of virtual and remote laboratories as online repositories for complementing traditional classroom education. Both direct and indirect feedback data from several users were analysed to assess the role of ICT-based virtual laboratories on different users. Perceived usefulness of virtual and remote labs and the shift in introducing blended approach towards improved laboratory training was highlighted by the change of performance in students using virtual laboratories as educational content.

As indicated in the feedback, the usage of virtual laboratories as a supplementary tool for regular laboratory training implicate a new trend in student-teacher interactions. Studies indicated that both teachers and students adapted to virtual laboratories implicating an increase in perceived usefulness of virtual labs in curriculum. In direct and indirect feedback, learners showed concept-based learning was augmented during virtual lab usage in the absence of an instructor. We also noticed that students who performed virtual laboratories were able to learn concepts of experiments in an instructor-independent manner indicating the self-organization abilities amongst students, reducing student-teacher interaction in a traditional classroom. Students preferred virtual laboratories as a pre-lab material to acquaint the basics of each experiment before practicing it in a wet lab. Our studies also showed enhanced learning outcomes amongst students, which implicated virtual (animations, simulations) and remote labs augment self-organized learning within traditional classroom learning. Feedback from students suggest that they learnt more from virtual lab exercises and they have indicated the prominence of repeatability to reproduce laboratory exercises. Student's direct feedback supported virtual lab as a novel self-learning tool that promotes their meta cognition, learning engagement, self-adaptability, and transfer of knowledge. Analysis of the pre-test and post test scores amongst the control groups indicated that by implementing virtual laboratories in classrooms, class average has been improving as compared to pre-test scenario. Also, the test groups (university level and pre-university level) scored better in the examination compared to control groups. Student's performance in a classroom with virtual laboratory exercises have shown significant improvements in their learning outcomes. A key outcome towards the relevance of virtual laboratories was consequent usage in the curriculum ensured a better academic performance.

We found the usage of remote labs as additional classroom material overcame some of the perceived inadequacy for facilities (in some rural campuses) for educating skillsets needed for research. Workshop participants from India's rural and geographically remote non-city regions perceived remote labs as a distant education tool for equipment training and as a platform that allowed repeated usage of devices beyond scheduled classroom hours. Some issues related to poor usability of the remote labs was correlated to technical issues and inconsistent network connectivity. Deployments suggest low-cost and feasible FOSS based implementation facilitate augmented teacher interaction and usage adaptability with our remote labs.

Some of the limitations of the study included looking at larger populations of both engineering and science students from different geographically distinct continents and varying backgrounds, in order to provide a more generalized understanding of how self-organized learning could be enhanced with the usage of virtual and remote labs. Also, in some cases pre-usage training on virtual laboratories is essential among teachers of diverse age groups. Studies indicate virtual laboratories cannot completely substitute existing educational institutes or replace hands-on laboratory courses. Immersive inclusion of such ICT techniques in education will enhance pedagogical roles of instructor-independent learning in universities and colleges dealing with a large student ratio.

Web analytics indicated that the number of virtual lab users has been increasing continuously throughout the year. Our virtual labs have 305327 registered users with a steady increase of new users per month. This anticipates the utility of this virtual laboratories project at a joint individual-enterprise scale. As Massive Open Online Courses (MOOCs) have gained momentum as learning environments, rapid usage acceptance of virtual and remote labs indicated these online labs facilitating augmented laboratory experience, and have allowed users to adapt to self-organize blended learning. Although evaluations will need other metrics and features, our approach to virtualization had answered many key results in establishing the virtual lab features such as teacher-independent/teacher-friendly approach to e-learning.

6. Conclusion

The study outlined design, implementation and deployment of virtual and remote laboratories in the field of science and engineering education. Local schools and other universities are implementing virtual and remote labs as a classroom component for laboratory skill training through our nodal center program. User data and web analytics indicates a large number of community college and University students from US, Europe and few users and institutions in Northern Africa as regulars indicating the explorable ubiquity as a generalised learning tool. We have already deployed regular usage with more than 100 institutions in India implementing this on a regular basis among their students. A future study will investigate what signifies as metrics for these novel methods in teacher-independent reflective learning practices.

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Figure 1

Architecture of remote laboratories.

The remote laboratories included a client-server architecture and was handled by the CAPVL platform.

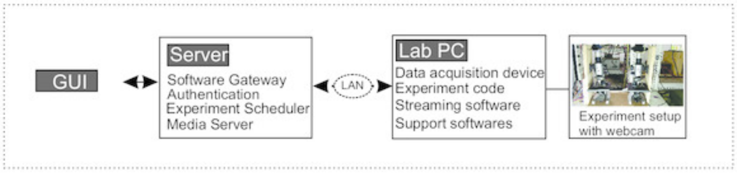

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Figure 2

Organization of CAPVL (virtual laboratory) platform for implementing and deploying virtual and remote laboratory experiments.

A. Component-level diagram of virtual laboratory experiments. B. Operational flow in virtual laboratory platform.

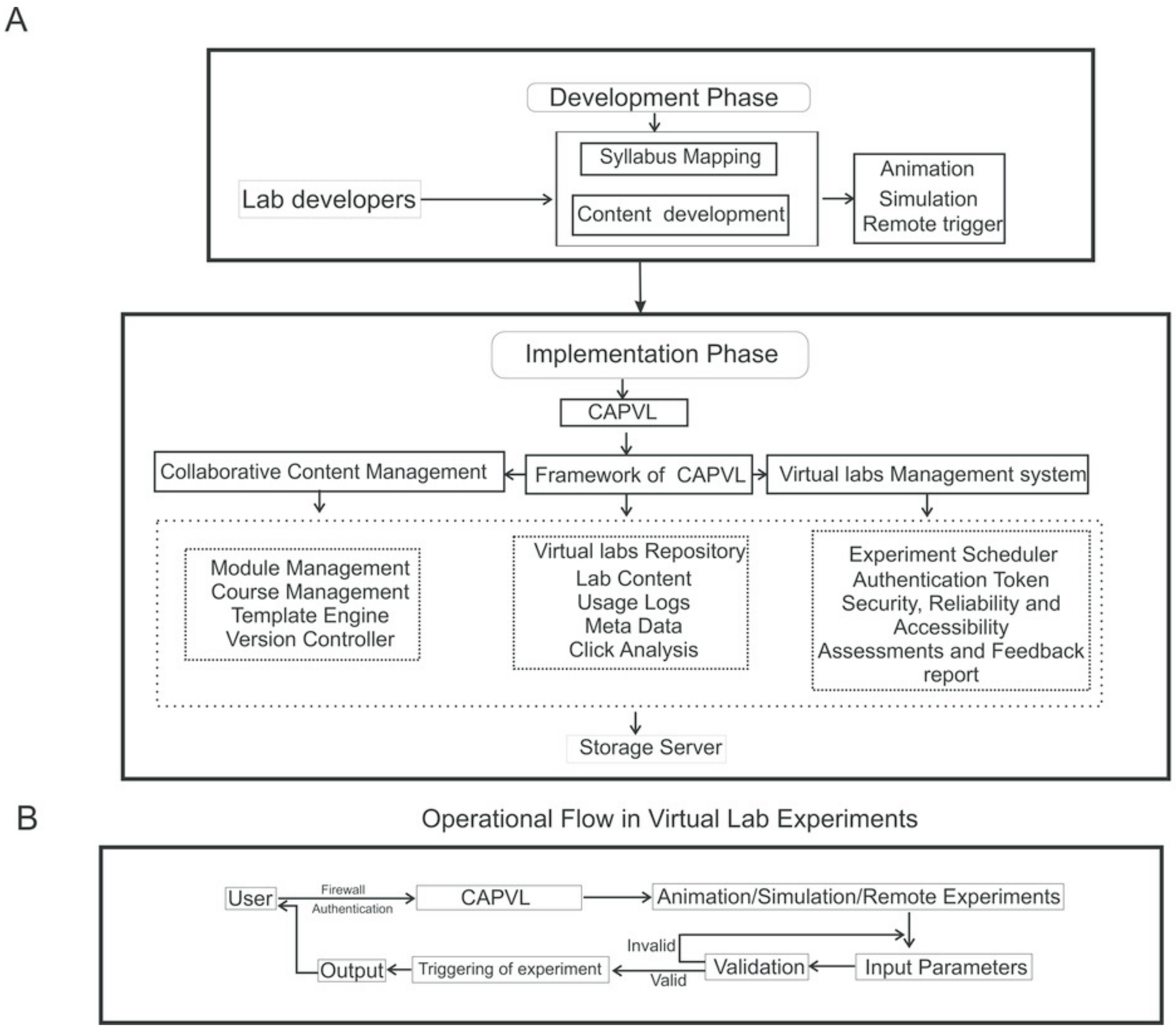

Figure 3

Feedback-based evaluation of virtual laboratories among student users.

Percentage scale analysis report was shown for each feedback question. Y- Yes, N-No. Y means that the users agreed positively on a particular question. N means that the user does not agree on that question, CS- Can’t say, means that the user neither said ‘Yes’ or ‘No’. Abbreviations – US – Usability, LE – Learning Engagement, SO – Self Organizing, MR – Memory Retention.

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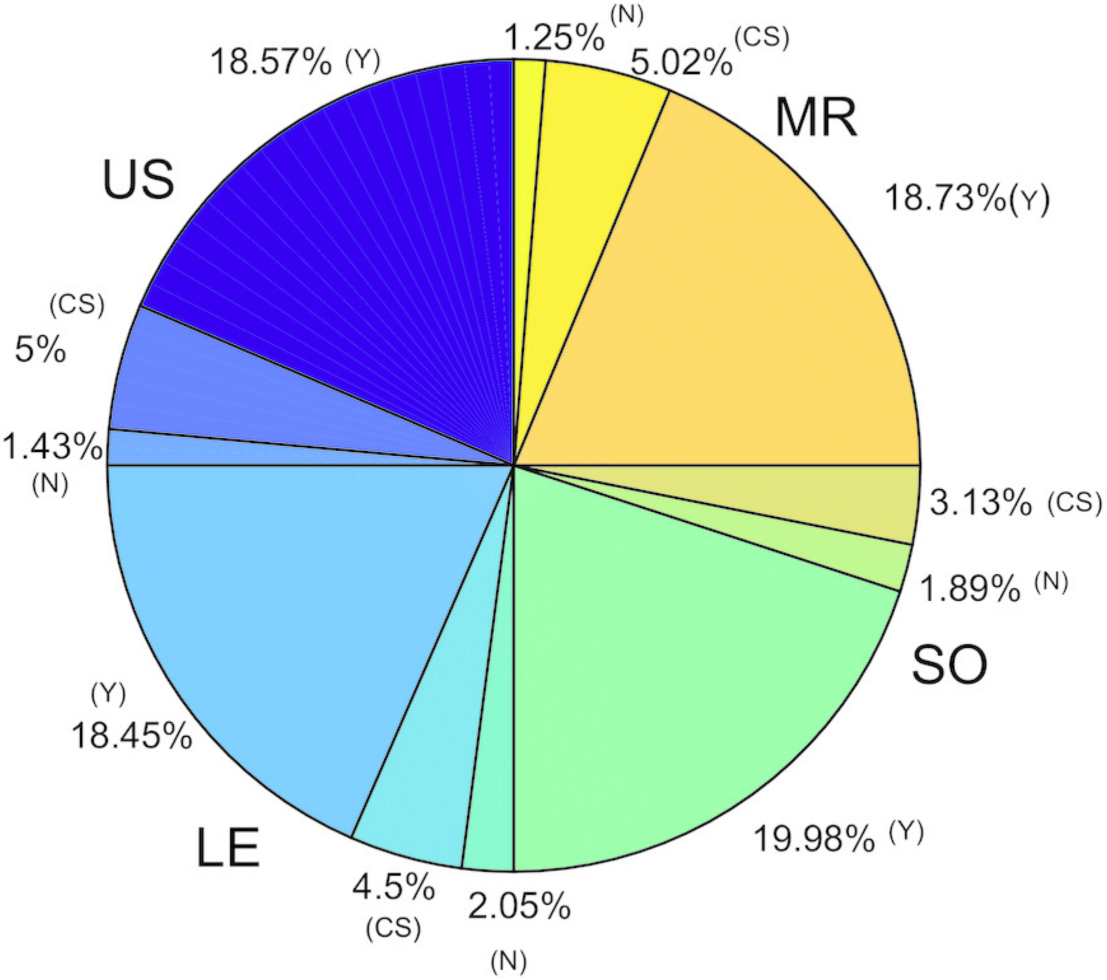
1.25% (N)
5.02% (CS)
MR
18.73%(Y)
3.13% (CS)
1.89% (N)
SO
19.98% (Y)
2.05% (N)
4.5% (CS)
LE
(Y) 18.45%
1.43% (N)
5% (CS)
US
18.57% (Y)

Figure 4

Remote laboratories as a distant education tool.

A. User feedback responses from remote laboratory usage by students in the context of a distant education tool towards enhancing biotechnology laboratory education. B. Online feedback data analyzed from distant learner's usage of an remotely controlled experiment.

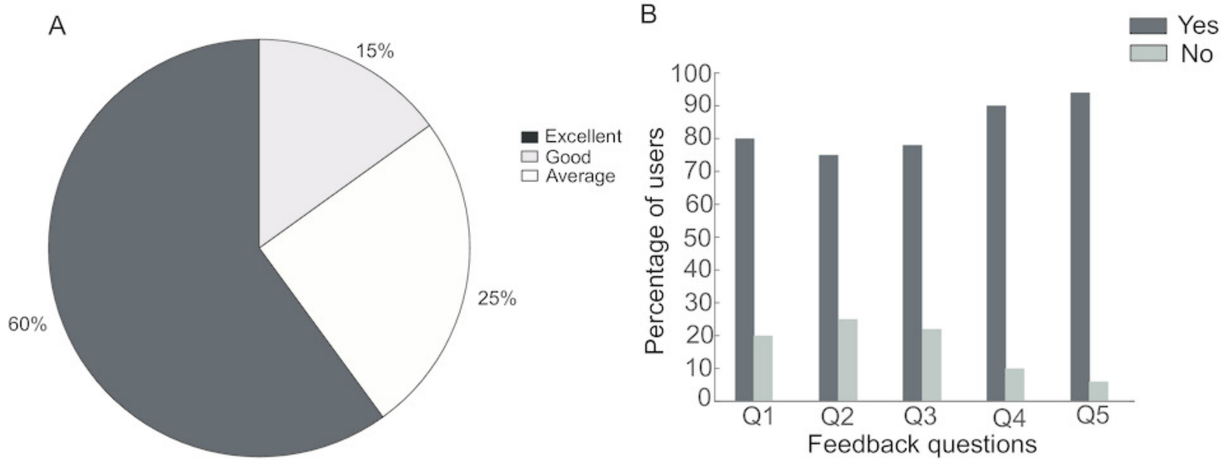
A
15%
25%
60%
Excellent
Good
Average
B
Yes
No
Percentage of users
100
90
80
70
60
50
40
30
20
10
0
Q1
Q2
Q3
Q4
Q5
Feedback questions

Table 1(on next page)

Virtual laboratory workshops conducted for teachers and students.

Direct feedback collected during onsite hands-on workshops.

<table>
<tr><th colspan="3">Workshop based evaluation</th></tr>
<tr><td>Type of lab</td><td>Number of student participants</td><td>Number of teacher participants</td></tr>
<tr><td>Biotechnology virtual lab</td><td>384</td><td>141</td></tr>
<tr><td>Biotechnology remote lab</td><td>194</td><td>93</td></tr>
<tr><td colspan="3">Online feedback</td></tr>
<tr><td>Type of lab</td><td>Number of feedback obtained</td><td>Number of feedback evaluated</td></tr>
<tr><td>Biotechnology virtual lab</td><td>> 300000</td><td>49800</td></tr>
<tr><td>Biotechnology remote lab</td><td>>5000</td><td>2500</td></tr>
</table>

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Table 2(on next page)

Usage and technology adoption analysis.

Usage and technology adoption factors analysed on student learners using Biotechnology virtual labs (TAM and OER survey models).

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Analysis factors	Research focus	Hypothesis
Usability (US) User interaction with computers	Computer literacy Easiness of usage Computers in education Interactive learning platform Supplementary classroom material	ICT would be a solution for providing better education.
Learning Engagement (LE) Student-student interaction	Curiosity to learn science Logical reasoning Constructivist thinking Increases motivation Learning faster	ICT helped to improve student -student interaction in a classroom.
Self-Organization(SO) Student centered learning	Control laboratory materials and equipment Creative thinking Autonomous learning self-assessment Time management	Virtual labs promote self-organized learning.
Memory Retention(MR) Student-teacher interaction	Perform better in real lab Score analysis Reduce examination stress	Virtual labs act as a platform for education anytime-anywhere without the physical presence of an instructor.

Table 3(on next page)

Online feedback survey.

Questions employed on virtual laboratory learners and users as part of the online feedback survey.

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Feedback questions	
Technical feedback	User experience feedback
To what did you have control over the interactions?	Virtual labs allow familiarizing with the basic laboratory techniques in par with regular theory classes.
How do you rate the online performance of the experiment?	Virtual labs can be used as a laboratory reference material.
Was the measurement and data analysis easy for you?	Virtual labs help to enhance, intensify and motivate user attention thus improving the scale of lab performance.
Were the results of the experiment easily interpreted?	Virtual labs help users to access costly and highly sensitive equipment.
Could you easily run the experiment without any interruptions?	Topics covered relevant to the courses in your curriculum.

Table 4(on next page)

Remote laboratories survey questionnaire

Questions included as part of the online feedback survey on users of remote laboratories.

Question	Feedback Questions
Q1	Do you think overall interactions included in remote labs are satisfactory to understand equipment control or experiment usage?
Q2	Were topics covered relevant to the syllabus at your institute?
Q3	Would you prefer including remote trigger experiments in your classroom?
Q4	The remote labs reproduce valid data realistically as in the case of traditional lab?
Q5	Do you think the content provided by remote experimentations was easily understandable even for distant learners?

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Table 5(on next page)

Construct measurement in TAM

Each TAM construct was estimated individually from user feedback.

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Analysis Factor	Questions for analysis	Cronbach's α (K12 students)	Cronbach's α (University level students)
Usability (US)	The usage of computers is an easy thing in the day to day life.	0.86	0.86
	Virtual learning as a technological medium that assist in the communication of knowledge in a particular subject.		
	Computer based learning provide individualized learning situations via animated experiments, simulations, emulations etc.		
	Virtual reality technologies are revolutionizing the current education system.		
Learning Engagement (LE)	Virtual labs enhance, intensify and motivate student attention towards learning.	0.81	0.86
	Virtual lab experimentation in science supports student-centered learning.		
	"The more you perform, the more you learn"- Rate your point of view about this statement.		
	Supportive instructional and assessment tool that improve cognitive and social behaviours of student groups.		
Self-organization (SO)	Virtual labs allow student to familiarize the basic lab techniques easily.	0.85	0.86
	Virtual labs train the students in the aspects of using laboratory equipment and reagents.		
	Content rich virtual lab is an important reference material.		
	Virtual labs help to follow standardized protocols without the presence of a lab instructor.		
Memory retention (MR)	"A picture is worth a thousand words". "The more you perform, the more you learn"- Rate your point of view about this statement.	0.80	0.85
	Virtual labs can be used as a pre-lab material.		
	Virtual lab experiments easily memorable than traditional method.		

	Referring virtual labs would help you to score high marks in your traditional lab exams.		

2

Table 6(on next page)

User performance in pre and post-test evaluation.

Evaluating user performance among virtual laboratory users.

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Study group	University level students			Pre-university level students		
Study Criterion	Pre-test		Post-test	Pre-test		Post-test
	Percentage of marks	Number of students	Number of students	Percentage of marks	Number of students	Number of students
Control Group	100	0	2	100	0	2
	90 - 99	0	8	90 - 99	0	7
	80-89	2	28	80-89	1	29
	70-79	11	42	70-79	15	37
	60-69	30	9	60-69	27	11
	50-59	38	7	50-59	35	10
	<50	15	0	<50	18	0
Test Group	100	4	Results tabulated for analysis	100	5	Results tabulated for analysis
	90 - 99	10		90 - 99	14	
	80-89	22		80-89	20	
	70-79	42		70-79	38	
	60-69	13		60-69	16	
	50-59	5		50-59	3	
	<50	0		<50	0	

Table 7(on next page)

Construct measurement in TAM among teachers.

Summary of construct measurement in TAM from Teacher’s feedback responses. Each TAM construct was estimated individually.

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Analysis Factor	Questions for analysis	Yes	No	Cronbach’s α
Usability of virtual labs in teaching (US)	The usage of computers is an easy thing in the day to day life.	85	15	0.80
	Virtual labs substitute for class room presentations in teaching.	82	18	
	Virtual labs could be used as examination component to assess user performance in a better way.	83	17	
	I will encourage my students to use virtual labs, so that I can reduce my time spend in preparing materials for students.	82	18	
	Virtual laboratories provide new inventions towards effective education supplementing class room teaching.	84	16	

Table 8(on next page)

Feedback response from college teachers.

Correlation in teacher’s responses for virtual laboratory usage in 2014 and 2015.

Questions for analysis	Teacher's Positive response (Yes) (Percentage)	Teacher's Positive response (Yes) (Percentage)	Pearson correlation coefficient
	2014	2015	
Virtual labs can be used as a substitute for class room presentations in the classroom teaching.	82	90	0.9020
Virtual laboratories provide new inventions towards effective educational supplementing the regular class room teaching.	82	90	
Virtual lab demonstrations are effective in an overcrowded classroom scenario.	78	80.2	
Virtual labs can be used as a supplement for laboratory education.	82	84.6	
Virtual labs can be used as an examination component to assess user performance in a better way.	78	79.1	

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