



Integrating Functional Genomics and Crispr-Based Inquiry into Undergraduate Life Science Education

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ABSTRACT

The development of genomic technologies has revolutionized both life science research and undergraduate education. The development of functional genomics, which focuses on gene functions and their interactions at the systems level, and CRISPR-Cas genome editing, which allows for precise and heritable genome editing, have become core technologies in modern biological disciplines. The paper aims to discuss the theoretical rationale for functional genomics and CRISPR-Cas genome editing technologies in undergraduate life science education. It is evident that functional genomics provides an integrated framework for understanding gene expression, gene regulation, and genotype-phenotype relationships. On the other hand, CRISPR-Cas and CRISPR-Cas-ML genome editing technologies provide an opportunity for undergraduate students to manipulate genomic DNA directly and to understand gene interactions without depending on transgenic approaches. The use of functional genomics with CRISPR-Cas genome editing technologies provides an opportunity for overcoming some of the major conceptual challenges facing undergraduate life science students. The use of these technologies at different levels of curriculum development provides an opportunity for making an impact in undergraduate life science education.

Keywords: *Functional genomics, CRISPR-Cas genome editing, genome editing, undergraduate life science education, inquiry-based learning, gene regulation, gene interaction networks, curriculum development.*

INTRODUCTION

The rapid expansion of genomic technologies has fundamentally changed life sciences research and education; the introduction of CRISPR-based gene editing into undergraduate courses and the more general incorporation of functional genomics into curricula are key examples. Functional genomics is the characterization of genes or gene segments in a comprehensive two- to three-hundred thousand-gene

manner-whole-genome investigation and experimental analysis of all functional determinants in a defined organism. CRISPR-based genomics describes technologies that use synthetic or programmed ribonucleoprotein systems to effect permanent, heritable changes in select sequences in the tractable genomes of living cells, using a variety of delivery vehicles and techniques (a twenty-three-thousand-gene characterization using CRISPR-Cas9-based technologies provides unprecedented insight into the regulation of metabolism). These technologies have revolutionized research and offer ample opportunities for education, yet meaningful engagement in both areas remains elusive; both functional genomics and CRISPR-based inquiry are relevant, prominent, and accessible in the curriculum from introductory courses through to final-year undergraduate study (J. Ruppel et al., 2019) (Walsh et al., 2017).

Theoretical Foundations

Functional Genomics: Concepts and Educational Relevance

At its core, functional genomics addresses the interrelationship between genes and their products across entire biological systems (see, e.g., Piontkivska, M., & Zaremba, M. L. (2011), at [Link] and (J. Ruppel et al., 2019). Compared to genome sequencing, which focuses on the structural organization of genes, functional genomic approaches explore the gene expression dynamics and the interactions of all gene products in a specified biological system (Piontkivska, M. et al. 2011). The methods of functional genomics are ideally suited for undergraduate-level education. When the integrative genome projects and underlying data started to emerge at the end of the 90s, experimental functional genomics, computational functional genomics, and bioinformatics became novel fields within biological science.

Functional genomics emerged in many branches of life sciences but gained the greatest attention in cancer research, plant science, and microbiology. The CRISPR/Cas and CRISPR/Cas-ML technologies find increasing application in functional genomics (Piontkivska, M., & Zaremba, M. L. 2011). Students at all levels are eager to participate in cancer research, plant science, and microbiology.

CRISPR Technologies and Educational Implications

A variety of techniques for characterizing, regulating, or controlling gene function exists, e.g. transposons, ribozymes, antisense RNA, siRNA, over-expression, gene silencing, loss-of-function, targeted replacement, and transcriptional control (see, e.g., Piontkivska, M., & Zaremba, M. L. (2011). These activities can be done at multiple life stages, from DNA through mRNA onto proteins. CRISPR/Cas and CRISPR/Cas-ML, however, allow students to move control one level higher: towards affecting directly-genome DNA sequences (Pal et al., 2022).

In addition, procedures for evaluation and analysis are provided. Evaluation modules simply analyze the presence of desired mutations, whereas analysis modules infer from genotype or phenotype information the major components of gene interactions or networks by modeling them as graph structures. The system has flexibility of construction and parallelism of operation. CRISPR/Cas and CRISPR/Cas-ML are among the few techniques where functional control of gene products can still be executed without either a wait for several rounds of cell division or employment of established pre-conditional transgenic systems (Abdurakhmanov, J., et al).

Most life-science undergraduate students have learned the fundamentals of genome/expression information, yet the majority find it hard to comprehend higher-order/holistic gene interaction and network systems involved in biology. At the moment, experimental investigation becomes far more complex than further theoretical interpretation (). Before students can achieve a systemic understanding of higher-order gene regulation, they need first to exert direct constrained control to verify basic one or two-order interactions. CRISPR/Cas and CRISPR/Cas-ML provide a timely and convenient means for them to realize such a need.

Inquiry-Based Learning in the Life Sciences

The current era of rapid developments in the life sciences necessitates that educators regularly revise undergraduate curricula (Ivanov, 2020). Instructional materials that remain relevant past the first few months following publication present particular advantages. Students are prompted to record their interests in the design of inquiry-based projects. A survey of eligible themes generally reveals a strong inclination toward agricultural research topics. While only the broad domain is specified, a selection of candidate projects aligned with specific themes can be assembled to facilitate direction. Preceding research has indicated that students commonly participate from the onset, engaging in format selection, deliverable types, and further refinements). Well-established formats identified as favorable by educators remain available for use. Social concerns surrounding the CRISPR technology are serious and hot topics continue to materialize in ongoing experimental implementation (situation as of 2022). Program assessment includes opportunities for greater engagement with the investigation description than earlier development stages.

Functional Genomics: Concepts and Educational Relevance

The term functional genomics broadly refers to the study of genome function and its effects on phenotype and biological systems through protein-protein interactions, RNA expression profiling, mutation analysis, and other systematic approaches. Related terms, such as interolog mapping and systems biology, emphasize systematic approaches involving multiple species, in which proteins or other biological macromolecules involved in similar functions or pathways can be identified in data from other organisms. Some historical surveys characterize functional genomics more narrowly as any experimental approach aimed at determining the functions of the approximately 30 000 putative genes in the fully sequenced genomes of higher eukaryotes (J. Ruppel et al., 2019).

The term never had nor did it aspire to a strict definition more than relating to resource sharing, acquisition, and derivation of functional information beyond that provided by sequence alone, particularly in view of genome sequencing efforts that revealed a large group of so-called orphan genes, whose function within the biological system remained to be elucidated. Despite the prolific literature with genomic in the title, no formal effort had been made to disregard pre-existing multi-species interactions simply because they predated available genomes, nor had any meaningful classification and differentiation of dedicated tools been undertaken for the much broader multi-species context. The scope of a subsided course in 1999 featured the non-redundant multi-domain protein database. Beyond functional genomics, educational experts have emphasized the utility of transcriptomics-based intelligibility of the substantial known protein target landscape associated with a sizeable contemporary armamentarium of small molecules and drugs (Pal et al., 2022).

CRISPR Technologies and Educational Implications

Cas9, a mega-Dalton endonuclease associated with CRISPR acquired immunity, and a series of synthetic guide RNA (sgRNA) molecules have revolutionized genetics and genome editing (J. Ruppel et al., 2019). Easily designed and delivered sgRNAs enable targeted modification of genomes in virtually all organisms. Rigorous scientific investigation of the technology is underway; educational institutions are introducing CRISPR-based inquiry into life science curricula as part of undergraduate research and course-based initiatives, illustrating how inquiry and research transcend conventional disciplinary boundaries (M. Sankaran et al., 2021). Classroom modules using CRISPR have emerged in a variety of organism models—from *Arabidopsis thaliana* to yeast. Engineering projects include amelioration of plant growth under nutrient stress, cellulose degradation, and Alzheimer's modelling. Approaches vary from single undergraduate laboratory periods to multiweek projects pursued independently or by teams of students (Pal et al., 2022). Detailed characterisation and troubleshooting investigations document a variety of CRISPR designs for use in experimental and industrial settings [table 1].

Table 1: Core Concepts and Educational Relevance of Functional Genomics and CRISPR

Concept/Technology	Description	Educational Relevance	Examples / Notes
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Functional Genomics	Comprehensive study of gene function across whole genomes (expression, protein interactions, mutation analysis)	Teaches integrative understanding of gene interactions and system-level biology	Cancer research, plant science, microbiology; suitable for undergraduate projects
CRISPR/Cas & CRISPR/Cas-ML	Genome editing technology using programmable RNA-guided nucleases to modify DNA	Allows students to manipulate genes directly, observe phenotypic outcomes, and understand regulatory networks	Projects include Arabidopsis growth, cellulose degradation, Alzheimer's models
Gene Manipulation Techniques	Transposons, ribozymes, antisense RNA, siRNA, over-expression, gene silencing, targeted replacement	Provides context for genome-level interventions and comparison to CRISPR	Students learn differences between indirect (transcriptional) vs direct (genome-editing) control
Systems Biology / Interolog Mapping	Study of protein-protein interactions across species	Highlights multi-species functional genomics approaches	Identifies conserved pathways and gene functions in different organisms
Inquiry-Based Functional Genomics	Projects using microarray data, gene networks, or CRISPR manipulations	Encourages hypothesis-driven research, student autonomy, and active learning	Modules adapted for lecture labs and small-group projects

Inquiry-Based Learning in the Life Sciences

Inquiry-based learning (IBL) is a research-informed approach to education that fosters active student engagement, autonomy, and deeper understanding of key concepts. The Living Systems faculty at the University of California, Davis, have written an insight that highlights opportunities for further integration of IBL in life science courses. A well-designed inquiry project underpinned by well-defined learning objectives affords all students the opportunity to act as scientists. Indeed, inquiry projects designed and implemented by students are happening in both a large lecture-based laboratory setting and a small human biology laboratory setting (J. Ruppel et al., 2019) ; (Walsh et al., 2017). An inquiry-based functional genomics project has been developed with the intention of using microarray data to formulate a testable hypothesis that addresses a relevant biological question. Sample curricular units incorporating inquiry-based CRISPR–Cas9 projects that engage students with different levels of experience are also available. These inquiry-based projects precede a broader introduction to functional genomics in the core course, thereby establishing a foundation and context for further learning. Additional examples and best practices will be provided to assist both instructors considering functional genomics and those wishing to introduce an inquiry component into standard laboratory courses.

Curriculum Design and Alignment

Many professional accreditation bodies delineate a limited student learning–outcome profile, often focused on foundational knowledge, key concepts, laboratory techniques, and scholarly practices (e.g., Society of Toxicology). Nonetheless, there still exists a desire among many biology programs to develop, share, and implement curricula responding to local institutional, faculty, and student needs while striving to integrate current science with scientific practice and inquiry. To realize this goal, a series of functional genomics and CRISPR-centric learning objectives and inquiry-based curricular elements were developed as contextualized treatment options aligning well with existing biology-life-science student learning-outcome prioritization. Such context-connected delivery pathways assist in meeting crucial science-objectives coverage (e.g., the “big ideas” specified by National Research Council (U.S.) and Position Statements articulated by American Institute of Biological Sciences) to address systematic biological-science programming—even when formal knowledge-by-design delivery is impractical or unanticipated.

Curricular content and component options were described, facilitating broad consideration and sharing of fungible, modular treatments. Highly genericized content and adoption-path strategy, emphasizing articulation, strove to optimize meeting the diverse concurrent curricular environments and local resource-infrastructure landscape characteristic of varied biology undergraduate programs. (Pal et al., 2022)

Learning Objectives and Outcomes

Student learning objectives, as articulated in the “Curriculum” and “Course-Specific Goals” sections of the BIOL 1110 course outline, represent broad, generalizable goals shared by many biology courses:

- Demonstrate an understanding of the core principles of biology and how these principles relate to life's processes.
- Develop practical skills necessary to conduct biological experiments and analyze experimental data.
- Demonstrate proficiency in the discipline's core vocabulary.
- Use inquiry-based activities to cultivate critical thinking and analytical skills.
- Engage with current biological issues in an informed and responsible manner.

Although not explicitly outlined, additional objectives emphasize the responsible use of technology and the ethical considerations of its application. These specific considerations-required by the university but often undesirably de-emphasized when not sequenced appropriately-emerged naturally from inquiry-based lessons focusing on CRISPR technology. Together, these objectives also align with the Biology Science Program Outcomes of Memorial University and the Expectations for Development in Discipline-Specific Knowledge and Skills outlined by the Society of Canadian Limnologists and the Canadian Network of Academic Librarians. Finally, they closely match several of the recently articulated Ten Essential Student Learning Outcomes for Undergraduate Life Science Education.

Module Architecture: From Core Concepts to Student-Driven Inquiry

Core concepts of functional genomics and genome editing technologies are presented prior to student-led projects. These modules reflect current scientific advancements and satisfy undergraduate outcomes. Coupling the investigation of gene, protein, and functional genomics with CRISPR assays enables the exploration of genome-scale gene function to probe fundamental biological questions. The CRISPR–Bacterial Artificial Chromosome (BAC) module exemplifies a student-driven approach within an inquiry-based framework and details project challenges to inform implementation across diverse institutional contexts (Ho Pao et al., 2021).

Functional genomics underpins understanding of gene structure and function in diverse biological systems, enabling genome-wide investigations of gene function, molecular pathways, and regulatory networks that control gene expression (J. Ruppel et al., 2019). Coupling functional genomics with CRISPR technology fosters student-led exploration of fundamental biological questions at the genome scale, allowing lab-relevant investigations of gene function, protein localization, protein–protein interactions, molecular pathways, regulatory networks, evolutionary conservation, and transcriptional control (Ziyav, A. A., et al). The CRISPR–bacterial artificial chromosome (BAC) functional-genomics module illustrates high-enrolment, student-driven inquiry within undisclosed core concepts and curriculum-external motivation. Students integrate published genome annotations and experimental results to formulate hypothesis-driven research questions and select gene–system combinations for investigation.

Sequencing and Pacing Across Undergraduate Programs

Most undergraduate biology curricula provide limited opportunities for extending both inquiry and research experiences outside of designated courses. Consequently, sequencing and pacing recommendations must take into account the variety of programs in which the proposed functional genomics and CRISPR-based investigation modules could be incorporated. While several institutions already offer a fully integrative

approach to undergraduate genomics education, it is anticipated that such an ambitious model may not yet be realistic for other North American programs. Therefore, a tailored sequence-of-introduction framework addresses the full range of introductory life science programs across the curriculum while conserving discrete periods for no-cost implementation, allowing for flexible yet congruent integration with existing materials. In general terms, the evolving structure presents a shared functional genomics module during the first semester of core biology [reinforcing the first module in part 3.1, where topics still represent requisite themes in all programs; courses equipped with appropriate resources may further extend the accompanying CRISPR-based inquiry to the second semester] followed by a range of options for further introduction to functional genomics, CRISPR inquiry, and extended research experiences; a multifaceted approach appeals to a diverse array of available platforms without overburdening students or accommodating inappropriate elements [table 2]

Table 2: Curriculum Design, Inquiry-Based Learning, and Learning Outcomes

Component	Description	Educational Purpose / Outcome	Implementation Notes
Curriculum Design	Aligns functional genomics & CRISPR modules with existing learning outcomes	Ensures coverage of core concepts, lab skills, and scientific literacy	Modular, flexible content adaptable to varied institutional resources
Learning Objectives	Core principles of biology, practical lab skills, proficiency in discipline-specific vocabulary, ethical use of technology	Develop critical thinking, analytical skills, and informed engagement with current biological issues	Linked to national and program-level science outcomes
Module Architecture	Prepares students with core concepts before student-driven inquiry projects	Builds foundational knowledge prior to hypothesis-driven experimentation	CRISPR-BAC module exemplifies high-enrolment, student-led inquiry
Inquiry-Based Learning (IBL)	Active student engagement through design, experimentation, and data analysis	Fosters autonomy, deeper understanding, and research skills	Projects vary in length, organism model, and complexity; integrates functional genomics & CRISPR
Assessment & Evaluation	Uses genotype/phenotype analysis, modeling of gene interactions, and project deliverables	Provides real-time feedback, reinforces experimental and analytical skills	Flexible evaluation; aligns with learning objectives and scientific practice

Distribution of effort across an entire program invites sideways chapter and partial module extensions without disrupting the overarching conceptual framework where access permits. Nevertheless, generalized recommendations should stimulate further discussion and adaptation to local circumstances. Neither prior functional genomics knowledge nor genome-engineering experience is necessary for teaching the proposed modules: comprehensive introductions consistently accompany the resources. Nonetheless, adoption of a part or segment typically requires independent preparation time on the order of one hour -additional extent typically remains optional within the overall maximum of twenty hours; detailed guidance for all modules, contingent on specific title selections, further limits preparation commitments to ten hours or less (Ziyaev, A. A., et al). Pan-organizational corpus of materials; adoption remains level facilitator awareness and rapid consensus conveyance (P. Buonaccorsi et al., 2011).

Assessment Strategies and Evidence of Learning

Evaluation of student learning in genomics at all levels must examine the effectiveness of various pedagogical approaches in fostering engagement, enhancing understanding of fundamental and emerging topics, and supporting the development of broader scientific competencies (J. Ruppel et al., 2019). For undergraduate life sciences, promoting student understanding of challenging CRISPR concepts necessitates identifying metrics that capture various dimensions of learning. A strategic model deploys flexible

approaches tailored to specific learning outcomes defined at the module level. Core minimums include offering learner-initiated examples illustrating CRISPR targets with requisite detail to assess broad comprehension, and securing single-cell RNA-sequencing data delineating gene expression under experimental conditions to gauge essential understanding across disciplines. Even for instructor-driven examples, student-led activities enriching individual modules can be integrated readily into experimental scaffolding. To meet the underlying goal of understanding structural relationships among CRISPR-related entities, a complementary model presents custom-designed 3D artifacts visualising physical, functional, and abstraction levels of target selection as a means of addressing widely observed misconceptions concerning this fundamental concept.

Laboratory and Simulation-Based Activities

The integration of functional genomics and CRISPR-based inquiry into undergraduate life science education can be implemented through a curriculum involving laboratory and simulation-based activities that span multiple programs and disciplines. These experiences provide authentic opportunities for inquiry that vary in level of difficulty and experimental choice. They promote deep understanding of the concepts and analysis within the functional genomics and CRISPR inquiry frameworks while exposing students to the interdisciplinary nature of contemporary biology. Although wet-lab experiences centred on functional genomics and CRISPR-based inquiry are common, ethical, safety, and practical considerations may prevent their adoption in some life science programs. In silico and simulation tools offer valuable alternatives for integrating teaching of these topics and inquiry during laboratory-based, computational, or modelling courses. Laboratory and simulation-based activities that reinforce foundational concepts of functional genomics, CRISPR technologies, and inquiry while incorporating student choice on experimental design and genetic targets can promote understanding and develop the associated scientific identity attributes. Examples of projects that incorporate active student participation and are suitable for implementation within a term or semester are available (J. Ruppel et al., 2019) (K. Vyas & A. Bernstein, 2019).

Wet-Lab Experiences: Ethical, Safety, and Practical Considerations

The rapid expansion of CRISPR technologies over the past decade has enabled a range of experimental designs that can now be implemented within undergraduate laboratory curricula. Approved by the European Union and the U.S. National Institutes of Health, research applications in human cells, tissues, and embryos remain prohibited in several regions. Nonetheless, additional approved research paradigms exist—such as testing altered codons—and the regulatory landscape can evolve (J. Ruppel et al., 2019). Ethical considerations, institutional mechanisms, and appropriate faculty oversight remain vital for all projects because researchers are often bound by promissory and contractual relevant regulations (Abdurakhmanov, J., et al).

Several basic principles for fair access and use of equipment, materials, and time can help mitigate competition among students. Faculty members are also tasked with providing adequate guidance throughout the project cycle, as students tend to pursue personal interests over instructional mandates or limits. In intensive environments, lessons can remain tightly structured while still maximising opportunities for independent exploration. Faculty can monitor schedules and deliverables and consolidate specific expectations across large cohorts. In addition, simplified achievement-check protocols allow for flexible timing that can fit diverse schedules and even optimize productivity during ad-hoc festival breaks (Walsh et al., 2017).

In Silico and Simulation Tools for Genomics

Functional genomics enables the characterization of genes in an unbiased manner and the determination of their sequence-dependent functions; such research is critical to understanding organismal biology, health, and disease (J. Ruppel et al., 2019). Genomic studies benefit from access to large datasets (DNA sequences, RNA-seq data, protein–protein interactions, and others) and bioinformatics tools for their analysis; public

databases continually expand the availability of these data to scientists and students. Several resources with specific functionality or broad integration assist researchers in analyzing genomic datasets; other platforms simplify genome editing, modeling, and validation, making them accessible to students involved in CRISPR-based inquiry and other genomic studies. Virtual laboratories that supplement or replace wet-lab courses provide freedom and flexibility for teachers to adapt to their institutional and pedagogical contexts while ensuring student learning about widely used genomics tools and data.

CRISPR-Based Inquiry Projects: Examples and Best Practices

The case studies selected for inclusion in the integration of functional genomics into undergraduate education illustrate different approaches to embedding inquiry-based, CRISPR-centric genomic projects into an established life-science curriculum, exemplifying desired best practices and aligning with educational priorities. Both case studies engage students with an authentic, open-ended investigative challenge designed to promote the development of scientific process skills, methodologies, and cognitive templates alongside conventional content knowledge. In addition, these examples reinforce the value of embedding experiential learning opportunities in first-year courses and affording students the choice of research direction (J. Ruppel et al., 2019).

Students analyse a transgenic *Arabidopsis thaliana* line to investigate the effect of a CRISPR-induced gene knockout on a growth-regulatory pathway of interest, acquiring skills in genome analysis, plasmid assembly, gene-target design, and material transfer from batch to biofilm cultures. The pedagogically favourable opportunity to contribute actively to genuine scientific research is thereby extended beyond early undergraduate programmes, into a first-semester course routinely attracting large numbers of participants without prior experience in laboratory practice, fieldwork, or statistical modelling.

Equity, Access, and Inclusivity in Genomics Education

Equitable access to science education depends on existing institutional infrastructure for delivering modern scientific curricula, alignment with local visions of collaborative undergraduate programs, and the scaffolding of active student engagement through diverse representation of scientists, educators, and learners involved in genomics and biotechnology innovation (Genomic Data Science Community Network et al., 2022). Genomics remains a significant focus of National Science Foundation investment, with direct relevance to environmental science, health equity, climate research, and agriculture, building on earlier initiatives that advanced modern DNA science and twenty-first-century learning outcomes. However, resource-rich institutions continue to contribute to inequities in access to pedagogically sound genomics instruction across undergraduate education. Factors such as prior mathematical preparation, language proficiency, social support, and access to collaborative, inquiry-based learning opportunities strongly influence student engagement in science education and long-term career development (Robbins et al., 2021). Strategic alignment of research support structures and flexible research participation pathways can enhance diversity in genomics education while increasing the societal relevance of research addressing contemporary global challenges (Sasmakov et al.).

Resource Allocation and Infrastructure

Selected CRISPR-based modules require uToolbox, a software platform for the instruction of bioinformatics genomics that automates data analysis while maintaining educational value. Utilization of uToolbox is restricted to universities affiliated with the Canadian Bioinformatics Workshops during calendar years 2020/21 and 2021/22. Another recommended software, Geneious Prime, is a commercial product offered at a preferential rate to educational institutions but incurs a cost. Both platforms require an adequate computer infrastructure (J. Ruppel et al., 2019). Open-source platforms such as Galaxy, Jupyter Notebook, and R minimize requirements for computer infrastructure; they are functional when combined with the particular tools and codes required for specific analyses. CRISPR-based modules permitting data analysis via these platforms can therefore be taught within curriculum segments constrained by available

infrastructure (Azimova, S., et al. 2023). Extended paleysfm analyses characterizing the G4-luc expression system can be conducted using either Galaxy or R in addition to an unsupervised Python exercise on transcription and fusion genes; these further CRISPR-bioinformatics analyses can be integrated into specific CRISPR modules according to institutional infrastructure. The engagement of bioinformatics tools to enable high-yield analysis and simultaneous code instruction is compatible with CURE attributes.

Inclusive Pedagogies and Diverse Representation

Diversity, equity, and inclusivity represent core values in the life sciences and undergird the institutional mission of the University of California (A. Sparks et al., 2020). Integrating functional genomics and CRISPR-based inquiry across the undergraduate curriculum presents an immediate opportunity to critically examine pedagogical practices for broader representation of culture, gender, and sexuality in the science canon, thus increasing accessibility and relevance for students in disproportionately impacted demographics.

Open Educational Resources and Collaboration

Establishing open educational resources (OER) and collaborating with other institutions can facilitate broader adoption of pedagogical approaches and increase resource accessibility for students and educators (Pal et al., 2022). OER modules developed at the University of California, Davis, introduce genome-scale functional genomics in the context of environmental exposure and facilitate exploration of gene function using CRISPR-based approaches (P. Buonaccorsi et al., 2011). Short modules, intended for use in programs across the curriculum, cover principles of DNA sequence analysis, systematic genome mutagenesis, and large-scale gene expression analysis. A course on CRISPR technology provides a self-paced overview of its applications in diverse fields, emphasizing a student-centered approach and accommodating users with beginner to advanced bioscience backgrounds (A. Vasquez et al., 2023). The course materials are freely available online under a Creative Commons license, enabling broad dissemination and opportunities to adapt the content for specific institutional needs (Sasmakov, S. A., et al).

Evaluation and Research on Educational Outcomes

Too little space is devoted to the evaluation of quantitative and qualitative educational outcomes for modules integrating functional genomics and CRISPR-Cas9 inquiry into undergraduate curricula. This section outlines potential metrics to determine educational success, longitudinal initiatives to gather data on uptake and effects of curricular changes, and strategies for sharing the results of educational inquiry with colleagues. Genomics education supports the timely integration of contemporary advances in understanding the genome and its role in the emergence of complex traits. A detailed operational framework is available for the implementation of genomics modules at diverse institutions. The current emphasis on large introductory courses instead of genomics modules makes functioning as a consultant impractical (D. Reeves et al., 2018) ; (J. Ruppel et al., 2019) ; (Walsh et al., 2017).

Metrics for Success in Genomics Education

Online methods and services offer multiple strategies to assess skill development among life scientists, such as pre- and post-tests, student reflections, peer evaluations, course evaluations, and the measurement of course-specific learning outcomes. The incorporation of key theme and tool-based assessments at distinct levels can also provide insight into student growth; ePortfolios document student work over time and facilitate the assessment of the knowledge that increasingly complex student datasets communicate. Course-based undergraduate research experiences can be monitored using the Survey of Undergraduate Research Experiences (SURE), which quantifies perceived student skills before and after specific research experiences (Hernandez et al., 2018) and informs potential curricular improvements (J. Ruppel et al., 2019) or course-to-course comparisons.

Longitudinal Studies and Curriculum Improvement

Educational transformations aimed at developing undergraduate knowledge and skills in genomics constitute crucial endeavours promoting student success in life sciences. Longitudinal studies focusing on functional genomics research integrated into a first-semester on-campus laboratory course underscore the significance of early course-based inquiry in enhancing retention and degree completion in science, technology, engineering, and mathematics (STEM) disciplines. Together with an expansion of other validated course-based undergraduate research opportunities, such experiential interventions consequently bolster genomic literacy and participation in advanced life science degree programmes (D. Reeves et al., 2018). Educational strategies must also integrate emerging technologies relevant to both life science research and practice. With genomic and CRISPR technologies at the forefront of major discovery sectors, deploying relevant inquiry at the undergraduate level becomes even more pertinent (Walsh et al., 2017).

Publication and Dissemination of Educational Research

Educational research can contribute to the scholarship of teaching and learning (SoTL) by investigating the effectiveness and impacts of adopting functional genomics and CRISPR-based inquiry approaches. An important venue for this work is the development and dissemination of instructional materials that illustrate the implemented strategies, provide implementation resources, and evaluate the effectiveness of the approaches in undergraduate teaching. During the exploration of functional genomics education in 2017, multiple professional-development efforts reaffirmed the need to investigate both pedagogical approaches and the complexity of the regulatory landscape around RNA-interference gene-expression control; the broader movement was considered an appropriate target for an educational SoTL research project (D. Reeves et al., 2018) as well. Classroom-capture video records of multiple mini-lectures developed for undergraduate audiences, including relevant core material, pedagogical motivations, and implementation insights, were made available via multiple archives and teaching-resource distributions for CRISPR-education efforts at both academic and international levels to address the scope and audience alignment topics (Walsh et al., 2017).

Implementation Challenges and Solutions

Though pedagogical innovations are exciting and rewarding, they may also instigate discomfort due to anticipated difficulties or consequences. Such concerns frequently arise when considering the adoption of educational practices that depart from or build on existing ones (J. Ruppel et al., 2019). Challenges noted by life sciences faculty contemplating the integration of functional genomics and CRISPR-based inquiry into their courses-and suggestions for addressing these challenges-were compiled to promote greater comfort with these strategies. The corresponding sections of instructional materials provides additional background for prospective adopters. Institutional Constraints. Numerous levels of structural support are needed to facilitate effective and sustainable implementation of the proposed pedagogies. Faculty contemplating inclusion of functional genomics and CRISPR inquiry into life science courses should therefore consider their institutional contexts, the existing opportunities and limitations these present, and potential approaches to promoting systemic change (Lopatto et al., 2014). Legislating educational change from the top poses its own difficulties; the weight and durability of existing regulations commonly stifle movement by faculty. Reported experiences suggest that neither top-down nor bottom-up change management alone is likely to be fully effective. Norm-shifting students have proven an additional catalyst for curricular change, enabling faculty to implement innovations more safely.

Faculty Development. Even if structural supports are available, many instructors confronted the challenge of moving beyond merely theorizing the proposed pedagogies to effectively enacting them in the laboratory classroom. Focused faculty development in both pedagogical advancement and practical implementation is vital for addressing this issue, yet many institutions lack the capacity for such professional support.

Sustainability and Scalability. Broad implementation likewise raises concerns about the sustainability of implementation. Course completion yields reports and insights that assist subsequent instructors, yet sustainability and scalability remain an institutional challenge. Under faculty promotion and tenure policies prioritizing traditional research publication, the absence of formal acknowledgment may deter instructors from attempting such innovations. Proposals to establish hubs for course exchange, faculty development, and cross-institutional preparation, while potentially beneficial, likewise struggle for implementation (Azimova, S., et al. 2023).

Institutional Barriers and Change Management

The implementation of functional genomics and CRISPR-based inquiry in undergraduate life science education requires effective change management at the institutional and departmental levels. Faculty often confront diverse obstacles to adopting novel pedagogies, and these barriers may vary across campus environments. Implementation challenges commonly cited in the literature include matching instructional innovations to curriculum requirements; addressing resource, operational, and staffing availability; managing faculty workloads; adapting to institutional policies and traditions; and maintaining alignment with departmental funding, evaluation, and reward systems (Lopatto et al., 2014). Intervening on a broader institutional scale, institution-wide support structures—such as pedagogical orientation programs, common institution-wide curricula, central laboratory or educational support units, distributed ownership models, and dedicated professorial chairs—can facilitate educational reforms in many campus contexts. Functional genomics and CRISPR-based inquiry emerge as important pedagogical innovations for life sciences instruction at the undergraduate level. The emergence of the field of functional genomics, which examines gene function through genome-scale experimental and computational techniques, presents a rapidly expanding new frontier for educational innovations in genomics. Such advances present significant opportunities to develop course-based undergraduate research experiences for the teaching of genomics that enhance student engagement and educational outcomes. Integrating functional genomics and CRISPR technologies within undergraduate curricula enables a substantial educational opportunity precisely at the undergraduate level.

Faculty Development and Support

Faculty development and support are critical for advancing research experiences in undergraduate education (Lopatto et al., 2014). Diverse barriers hinder the adoption of research-based instructional strategies, including those related to faculty motivation, training, confidence, time constraints, and administrative support, along with institutional culture and local infrastructure. Strengthening faculty development opportunities can expand participation in research-guided pedagogy, facilitating the integration of functional genomics and CRISPR inquiry across life science courses and programs.

Undergraduate research promotes cognitive, personal, and professional development, shapes science career decisions, and fosters active learning. Educational models linking teaching and research throughout the curriculum can enhance engagement and retention; curricula encouraging broader participation and associating teaching with research in laboratory settings improve both. Well-supported, institution-wide undergraduate research initiatives create a community of practice that accelerates scholarly engagement and developmental activity while sustaining long-term growth. By systematically integrating genomics and bioinformatics across the curriculum, programs at Michigan have instead enriched life sciences education and strengthened the inquiry approach to teaching (Sasmakov, S. A., et al).

Sustainability and Scalability of Programs

Functional Genomics and CRISPR-based approach are forefront of contemporary biological sciences. Both disciplines are also excellent examples of open science. Globally, only 2.5% of scientists publish the majority of their work as preprints, but this figure rises to 12% in biotech and to 43% in CRISPR/Gene editing disciplines. As Genomics involves forward-looking technologies, Genomics curriculum at academic

level needs to be re-defined e.g. course objectives, course components, instructional methodologies etc. (Lopatto et al., 2014). Sustainability requires targeted infrastructure investments and support, while scalability hinges on faculty experience, the breadth of institutional adoption, and alignment with the broader curriculum (D. Reeves et al., 2018).

Conclusion

Functional genomics and CRISPR-based inquiry are poised to transform undergraduate life science curricula. Genomics, a discipline with profound implications across research, biotechnology, and health, is embracing the exploration of biological function. This shift is evident not only in the proliferation of experimental resources but also in the emergence of large-scale collaborations. The CRISPR revolution, offering genome engineering tools with unprecedented simplicity and specificity, is a direct result of genomics-driven exploration. Before CRISPR, progress in genome editing was constrained to specific organisms, requiring substantial time and effort for implementation. Today, student-directed genomics inquiry is widely accessible and rapidly expanding. Developed in diverse contexts-genomics, annotation, gene function, evolution-CRISPR provides an exemplar for integrating content areas with established pedagogies, thus broadening the appeal of accompanying pedagogies. Genomic exploration is increasingly content rich, shifting from gene identification and symbolism to gene function and organismal biology. Genomics and CRISPR are hence becoming widely sought, module-and course-level components, with the transformative potential to catalyze broad, deep change across life science curricula (Abdurakhmanov J. et al). Rigorous evaluation and documentation accompany many of the completed integrations. Five curriculum models spanning diverse curricula have emerged, with accompanying assessment metrics informing iterative improvement. Outcomes from a CRISPR-based inquiry module administered across four majors at an R1 institution demonstrated significant gains in student understanding of CRISPR, experimental design, hypothesis generation, and genome editing. With additional progress on resource development, numerous active collaborations, and interest from an expanding number of institutions, national repositories are anticipated that house pedagogical and curricular materials alongside metrics for gauging implementation fidelity (Sasmakov S. A. et al). Reviews of these materials remain invited. Systematic investigation of the contribution of integrated pedagogy to student learning and an inclusive approach to active-extension, -adaptation, and -application of the developed materials at a broad range institutional levels continue in parallel.

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