RESOURCES *for the* FUTURE

Strategy for Promoting Interdisciplinary Solar Geoengineering Research in India

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About the Project

The Resources for the Future Solar Geoengineering research project applies tools from multiple social science research disciplines to better understand the risks, potential benefits, and societal implications of solar geoengineering as a possible approach to help reduce climate risk alongside aggressive and necessary mitigation and adaptation efforts. The project began in 2020 with a series of expert workshops convened under the SRM Trans-Atlantic Dialogue. These meetings resulted in a 2021 article in Science that lays out a set of key social science research questions associated with solar geoengineering research and potential deployment. The Project followed this with additional sponsored research, including a competitive solicitation designed to address research areas highlighted in the Science article. This paper is one of eight research papers resulting from that competition and supported by two author workshops. A key goal of the solicitation and the overall project is to engage with a broader set of researchers from around the globe, a growing number of interested stakeholders, and the public.

About RFF

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Sharing Our Work

Abstract

According to the latest IPCC Working Group I report (2021), changes in the climate in recent decades are widespread, rapid, intensifying, and unprecedented in at least the last 2,000 years. The global mitigation efforts under the Paris Agreement have been inadequate to reach the target of stabilizing warming below 1.5°C. Thus, it is likely that interest in solar geoengineering (SG) as an additional option to address climate change may increase in coming years. The latest IPCC Working Group II report (2022) concludes that SG could offset some of the effects of increasing greenhouse gases (GHGs) on global and regional climate but also notes large uncertainties and risks involved in large-scale deployment of SG. In this context, we assess the need for promoting SG research in India. We conducted an expert opinion survey of mainly researchers and a few individuals from government departments and civil society members who have some level of expertise in climate change and knowledge of SG. A literature review, examination of funded research projects, and survey results indicate very limited research in India on SG, and even more limited social science research. SG research in India is largely focused on modeling the climate hazards, and government support for research (currently only from the Department of Science and Technology) is very limited.

The survey indicates that a majority of experts in India believe that SG research should be a priority area, with overall support for a national policy focusing on modeling, risk and im-pact assessments, and policy analysis. A majority also indicate that the government departments should be the dominant funding agencies for research and international collaborations should be encouraged. The survey highlighted the need for transparency, public consultation, disclosure of all SG research, and monitoring by a government interministerial committee. Finally, respondents indicated a need for a governance protocol and international collaborations due to the risks involved and transboundary nature of impacts.

Contents

1. Introduction

According to the 2021 IPCC report, because of human activities, such as fossil fuel burning, agriculture, and deforestation, the global mean surface temperature has increased by 1.1°C in 2011–2020 since the preindustrial period (1850–1900). The rate of warming in recent decades is unprecedented in at least the last 2,000 years and has affected nearly every region worldwide. Many of the extreme events observed recently are equally unprecedented. The World Meteorological Organization, in the "State of the Global Climate—2021," reports that the past seven years have been the warmest seven years on record. In 2020, CO_2 concentrations reached new highs (422 ppm in May 2022). Exceptional heatwaves, unprecedented floods, droughts, forest fires, etc., in different parts of the world are breaking records. Even if all the commitments made at the Glasgow Climate Summit are implemented (which is unlikely), the world will still cross 1.5°C before 2040 and the 2°C target in this century. Mitigation (emission reduction plus GHG removal) and adaptation are the two major strategies to address climate change. In the most likely event of not meeting the Paris goals, the world may experience more unprecedented climate extremes and face a catastrophe or emergency, if it has not already.

In a scenario where mitigation efforts are inadequate, solar radiation modification (SRM) could be one of the emergency response options to avoid some severe impacts of climate change. SRM or SG are deliberate, large-scale climate intervention or engineering approaches that work by reflecting more sunlight back to space. These approaches are proposed as potential supplements to deep mitigation. SG has few backers and more passionate opponents, who fear that research into SG will delay climate mitigation actions. SG could involve risks to human and natural systems and raise several ethical, moral, equity, legal, and justice questions. Thus, there is a need to develop a full understanding of all aspects of SG; scientific, technological, socioeconomic, governance, cost–benefit, ethical, equity, and legal.

The latest IPCC Working Group II report (2022) concludes that "SRM could offset some of the effects of increasing greenhouse gases on global and regional climate, including the carbon and water cycles." Further, there is suggestion that some SG technologies could, if used appropriately, substantially reduce the adverse impacts of climate change in most parts of the world (Keith and Irvine 2021). According to MacMartin et al. (2018), if mitigation proves insufficient to limit the rise in global mean temperature to less than 1.5°C above preindustrial levels, limited SG deployment could reduce climate damages. Reynolds (2019) concludes that SG may offer an opportunity to reduce climate risks but also warns of substantial uncertainties and risks. Keith and Irvine (2021) identify three key challenges for SG as an excuse for inaction on the fossil fuel front, the risk of unilateral action by a country with transboundary implications and termination shock, and long-term commitment for deployment (if it is stopped when GHG concentrations are high, temperatures could rapidly recover, leading to large rates of warming in the next few years).

India is a large developing country, with about 1.3 billion people, and nearly 70 percent of its population depends directly on climate-sensitive sectors, such as agriculture, fisheries, forests, mountains, and coastal regions. According to a global assessment by GermanWatch (Eckstein et al. 2021), India is one of the countries with the highest risk index for climate change. India is already experiencing unprecedented climatic events, such as extreme heatwaves and floods. Thus, given its size and vulnerability to climate risks, it must develop a good understanding of the natural science, social science, legal, and governance aspects of all solutions to climate change, including SG.

IPCC (2022) highlights many uncertainties that need to be addressed as soon as possible, as some countries may decide to experiment or deploy SG technology to counter a climate catastrophe or extreme. It is necessary to develop an understanding of the current state of research on natural science and social science aspects and suggest a strategy to promote interdisciplinary research. Thus, India could initiate studies, analyze, understand, discuss, and debate the pros and cons. We assess the state of Indian science and knowledge about the various aspects of SG research with the following objectives.

1. Review the state of social and natural science and interdisciplinary SG research to identify gaps and barriers.
2. Identify the need and rationale for interdisciplinary research involving natural and social scientists, to assist SG policymaking in the Indian context.
3. Identify the potential and opportunity to promote interdisciplinary SG research involving natural and social scientists.
4. Suggest institutional arrangements to promote interdisciplinary SG research.

In this paper, no attempt is made to recommend SG deployment, suggest a policy on behalf of the Indian government, or consider any legal or governance aspects. Further, in this paper, the intention is not to discuss the promotion or discouragement of SG technology, and no attempt is made to develop a national policy or governance system or research protocol; these are beyond the scope of this report. The focus is on developing an initial understanding of the state of knowledge on SG research in India.

2. Methodology

Since no readily available data exists on the extent of research and knowledge generation on SG in India, in particular on the natural science and social science aspects, it was necessary to first review existing literature and conduct a survey of the stakeholders involved in SG research in India. The methodology adopted for assessing the state of natural and social science research, the institutions involved, barriers, and potential opportunities for promoting SG research in India are as follows:

Review of research programs, projects, publications, and funding, based on websites and annual reports of funding and research agencies and a literature survey, and reports of workshops and conferences in India.

Review of private-sector and external funding, based on a survey of annual reports and websites of corporations and international agencies.

Survey of key stakeholders, particularly SG researchers: A questionnaire on various aspects of SG research was developed and sent to climate change researchers, including IPCC authors from India. Some respondents may not be directly involved in SG research but are familiar with the role of SG in addressing climate change. Other stakeholders, such as staff of government departments funding SG research and a few civil society organizations, were also included. The sample was selected by identifying the climate change experts in India, especially those involved in IPCC assessments, climate negotiations, and officials in central government ministries that fund climate change research. The sample included physical, biological, and social scientists and science administrators. It is challenging to categorize researchers working on climate change into natural or social scientists. Most climate scientists are also aware of the social science angles of climate change, as evidenced by IPCC reports, where authors assess several aspects of the issue. Thus, we did not categorize respondents as natural or social scientists. Finally, given the limited number of researchers directly working on SG in India, we invited all climate change experts to respond. About 50 experts were identified, and about 30 responded in the predetermined time frame. Table 1 shows the sample size and distribution of the respondents; the majority are academics, of which many are IPCC authors.

Table 1. Respondents to questionnaire on SG research in India

Category	Number of respondents
Academics: scientists and professor	20
Representatives of government departments	3
Civil society organizations and consultancy firms	7
Total number of respondents	30
IPCC authors	6

2.1. State of Natural and Social Science Research on SG and a Strategy to Promote Interdisciplinary Research in India

According to Bala and Gupta (2017), SG could be an option to offset some effects of climate change. Many research papers have been published by both natural and social scientists on SG feasibility, effectiveness, costs and risks, and ethical, legal, social, political, and governance dimensions. Most of this research is conducted in the developed world, with very little research or discussion in the Global South. The majority focuses on climate modeling, for which the Department of Science and Technology (DST) is the main funding source in India through its support natural and social scientists.

2.2. Status of Indian Research and Publications Since 2015

Several research papers and articles in magazines on SG have been published in India in recent years (Table 2). We discuss the publications since 2015. According to our review, there are about 20 natural science papers and six social science papers, largely focused on governance, but no paper considers both science aspects. We find six conference or workshop proceedings, four by the Council on Energy, Environment, and Water (CEEW) and two by the Indian Institute of Science (IISc), along with one book chapter by CEEW and six articles (opinion pieces) in environmental magazines, such as *Down to Earth*, and newspapers.

SG modeling: SG modeling studies in India have investigated the changes in summer monsoon precipitation (Krishnamohan et al. 2022), extremes in temperature and precipitation (Muthyala et al. 2018a,b), the global and tropical water cycles (Modak and Bala 2014; Nalam et al. 2018), and terrestrial plant productivity (Krishnamohan et al. 2019) for reductions in incoming solar radiation (Kalidindi et al. 2015), stratospheric aerosol injections or prescribed sulfate aerosols in the stratosphere (Krishnamohan et al. 2019, 2020, 2022), marine cloud brightening (Bala et al. 2010), and land surface albedo modifications (Bala and Nag 2011). The modeling tool used is the NCAR CESM framework, and simulations have used the Community Atmospheric Model (CAM3, CAM4, and CAM5) coupled with a mixed layer model. Bala and Gupta (2018, 2019) and Bala et al. (2019) provide a review of these studies.

Gaps in SG research: Most relevant studies in India have used single-climate models, so their estimation of climate benefits and hazards have large uncertainties. The uncertainties and assessment of robustness of the results using multiple climate models have not been quantified, nor have the SG impacts on human and natural systems in India been assessed. Only a couple of studies address SG impacts on crop yields in India (Yang et al. 2016; Singh et al. 2020). Impact assessment is entirely lacking for other sectors, such as forestry, fisheries, water resources, air pollution, and human health, as is research on social science issues, such as the ethics, justice, legality, and politics of SG.

Table 2. Publications on SG Since 2015

Publications	Focused on		
	Natural science	Social science or governance	Natural and social science
Research papers published	20	6	
Conference and workshop proceedings		4 by CEEW	2 by IISc
Book chapters		1 by CEEW	

2.3. Extent of SG Research in India: Natural and Social Science

Extent of general research (Figure 1a): Seventy-three percent of experts surveyed believe that general research is very limited. A quarter believe that no research of consequence is happening on SG in India.

Extent of social science research (Figure 1b): We do not define social science, as we believe that most climate researchers and policymakers are aware of several dimensions of climate change, including social science aspects. Social science includes governance, and we identified a few reports on these. Sixty percent of respondents believe no research of consequence is happening in India, and 37 percent believe that research is very limited.

Barriers for social science research (Figure 1c): According to the experts, the barriers or limitations for research and development (R&D) on social science aspects include a lack of awareness of them, of SG, absence of multi-institution and multiexpert teams, and lack of funding. A few experts are directly involved in SG research, including social science.

Figure 1a. Extent of research on SG in India (percent)

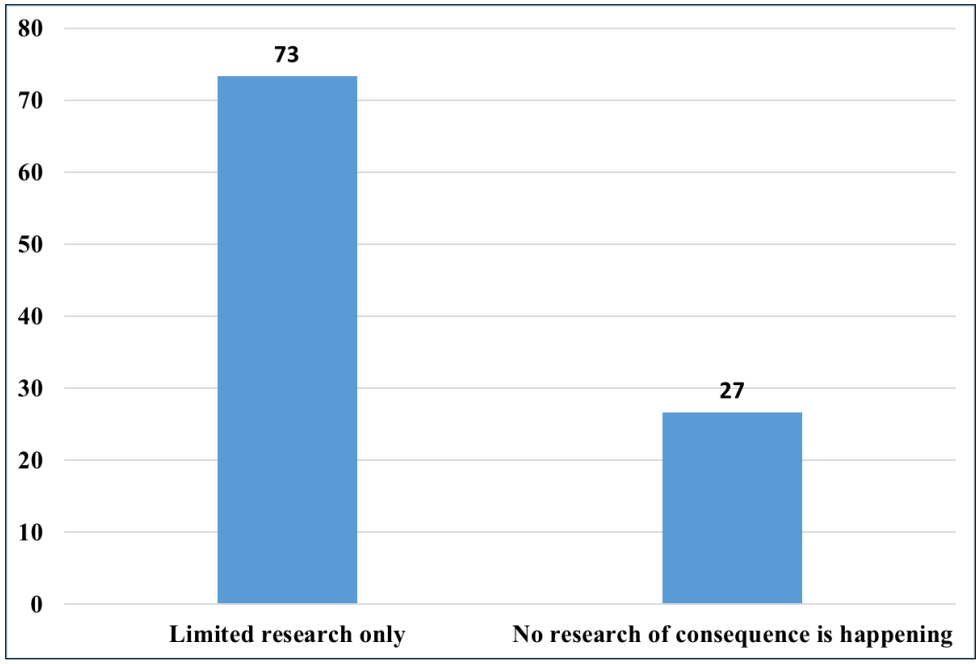


Figure 1b. Extent of social science research on SG in India (percent)

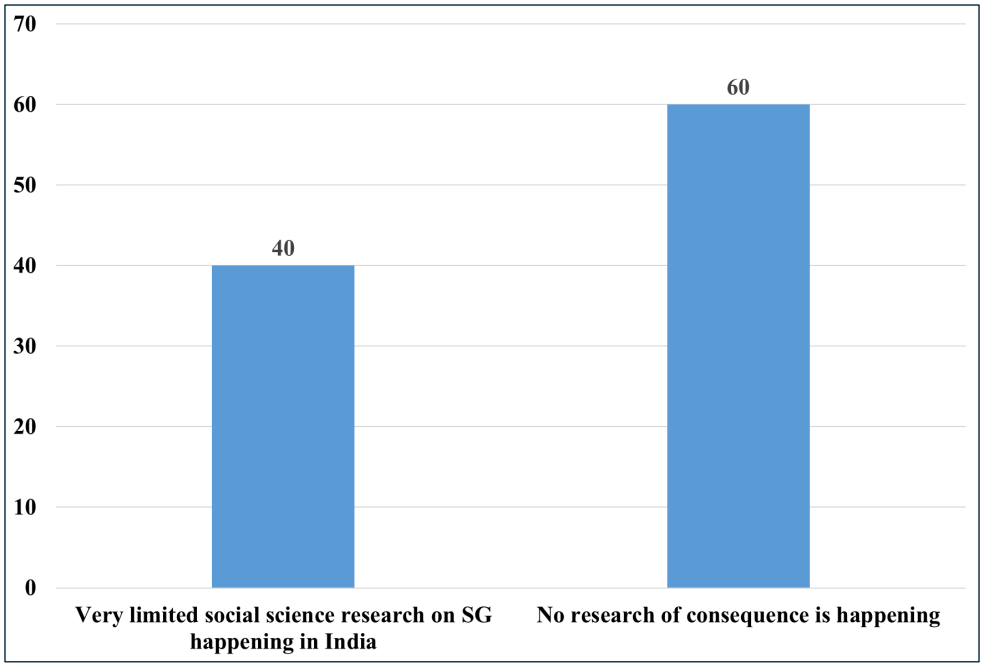
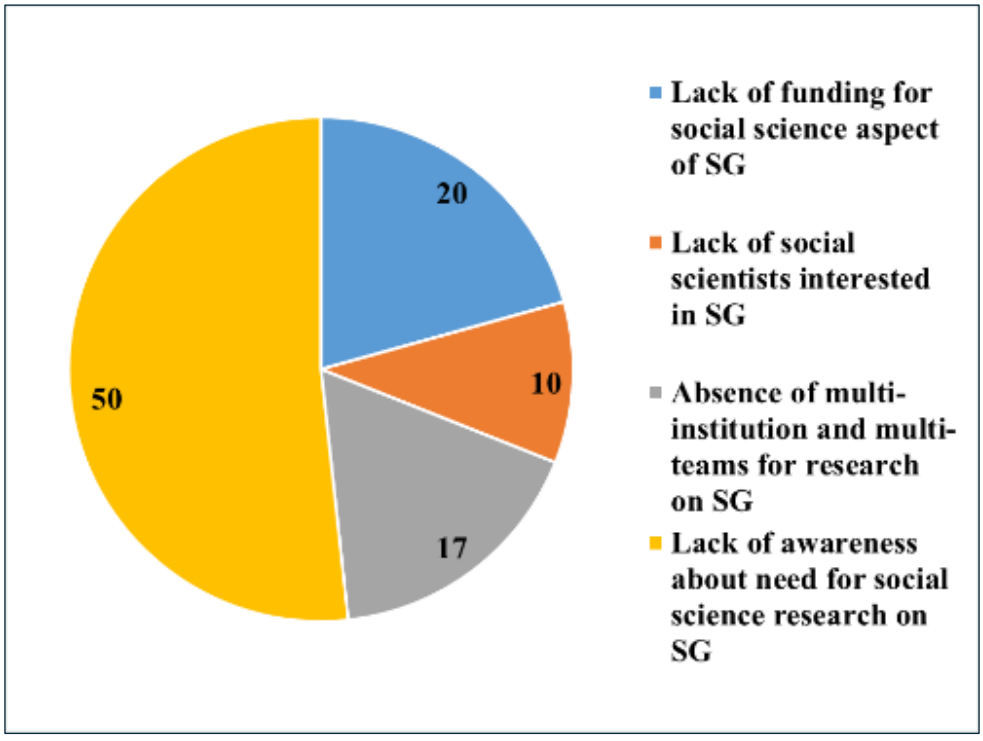


Figure 1c. Barriers for social science research on SG in India (percent)



2.4. Need and Rationale for SG Research, Government's Role, and Research Institutions

Purpose of research (Figure 2a): A third of respondents identify the need for Indian research to be on par with developed countries, and a third say that climate change is a national security issue, especially as it could impact food and water security in India. About 20 percent highlight the need to develop expertise on SG research for any future applications.

Role of government in supporting research (Figure 2b): A majority (53 percent) of respondents highlight the need for government support on a priority basis, and about 43 percent also support it but not on priority basis.

Government support for pilot SG projects (Figure 2c): The majority (77 percent) of respondents highlight that government should support pilot projects on the assumption that other countries may undertake these small-scale field experiments with transboundary implications; the rest suggest no need of such support. It may be noted that a few pilot projects have been attempted in different parts of the world but without success.

Institutions for conducting research (Figure 2d): The overwhelming majority of respondents believe that public institutions, such as research institutes, universities, and national laboratories, should dominate SG research; a few felt that other agencies, such as corporations, consultancy firms, and nongovernmental organizations (NGOs), could also be involved.

Figure 2a. Purpose of research on SG in India (percent)

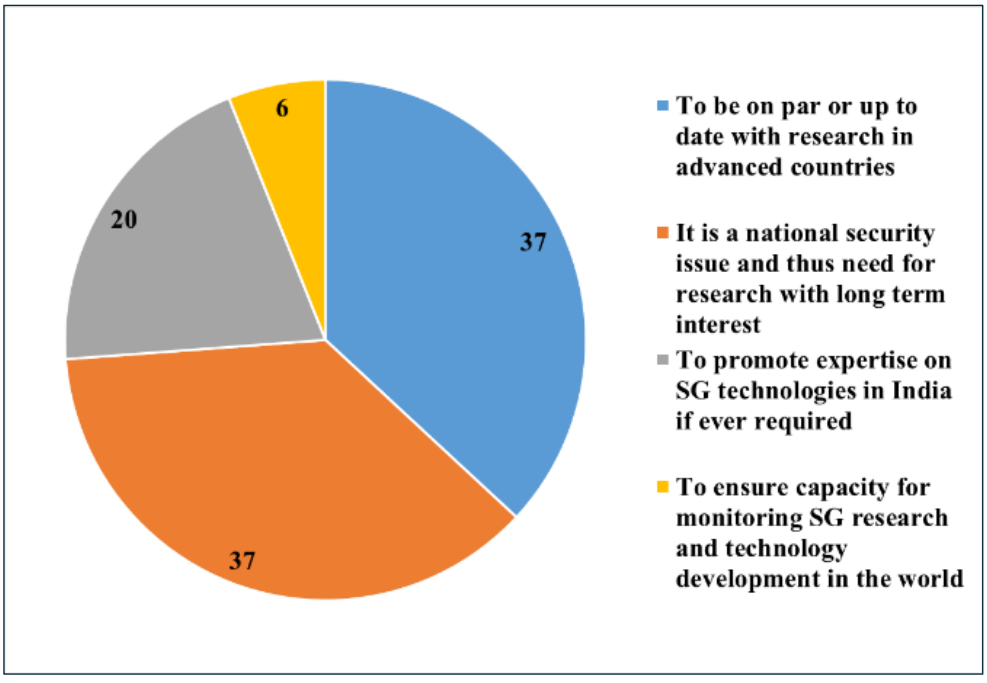


Figure 2b. Role of government in supporting SG research in India (percent)

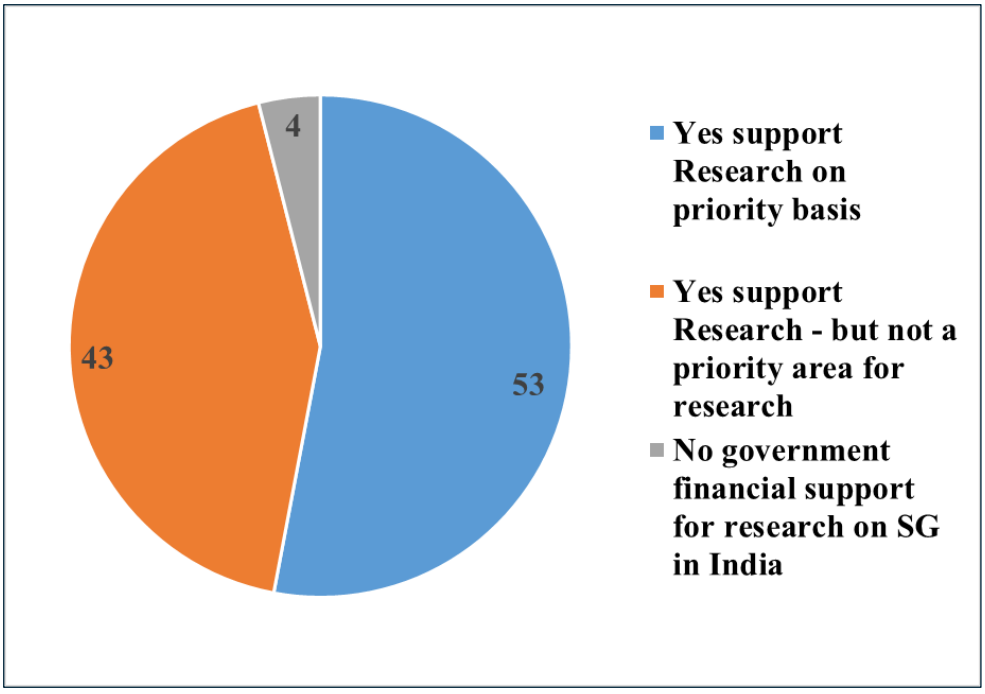


Figure 2c. Support of government of India for pilot SG projects in India (percent)

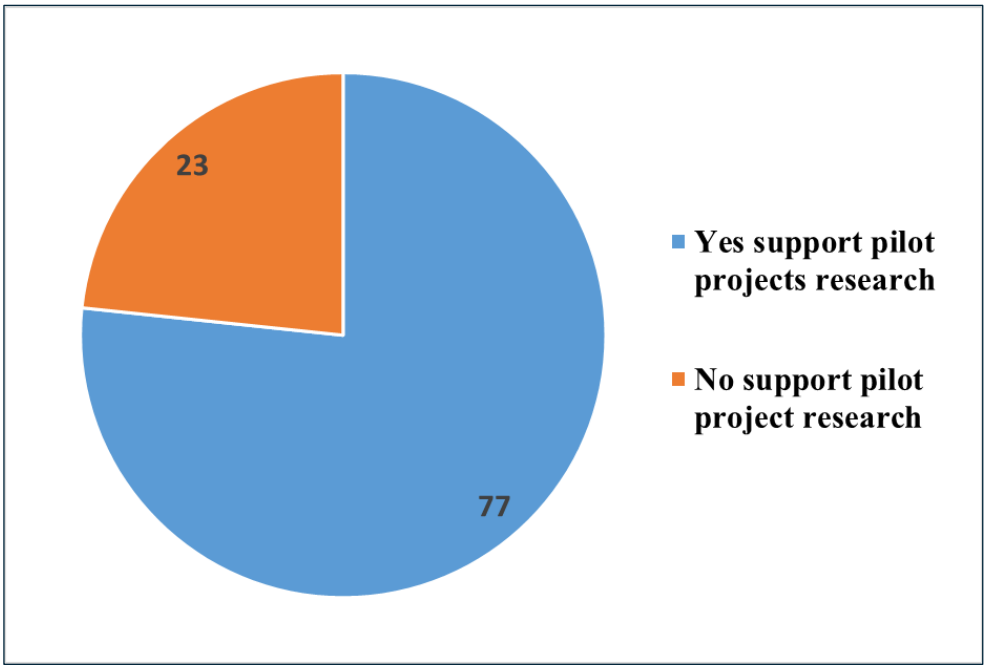
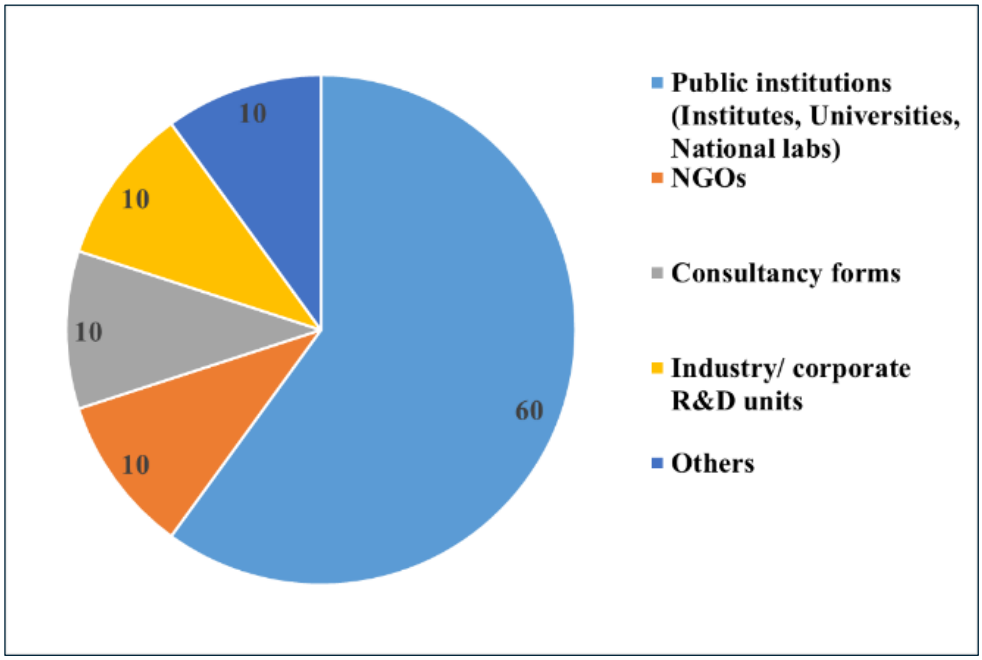


Figure 2d. Institutions for conducting SG research in India (percent)

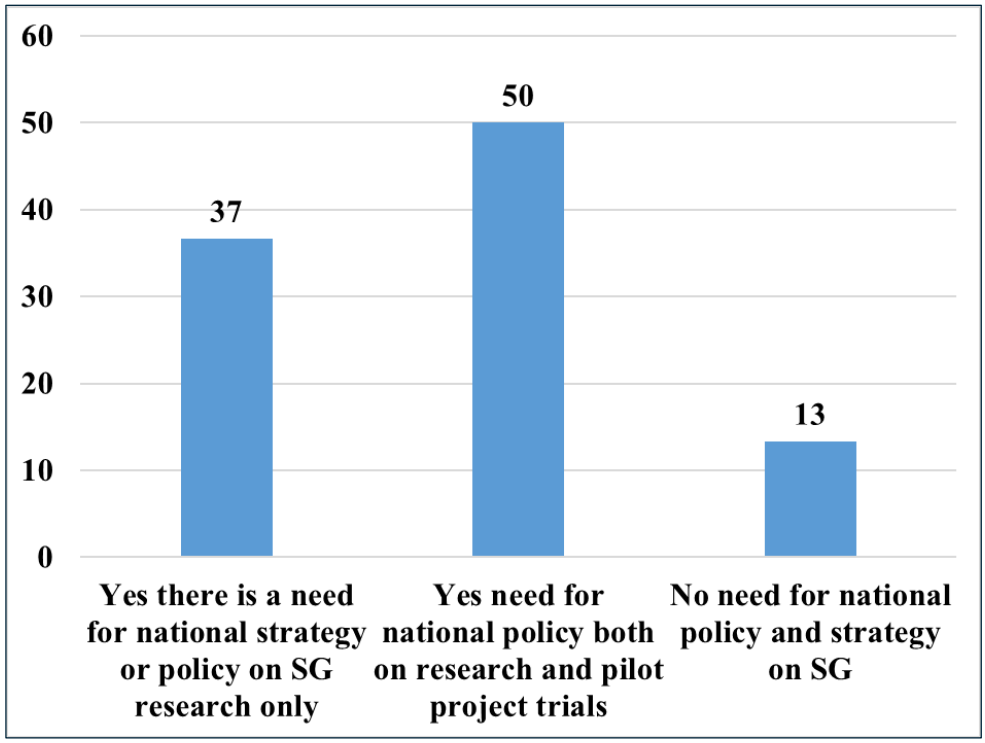


Note: "Others" includes any capable private organization or agency

2.5. Need for a National Policy

Regarding a dedicated national policy (Figure 3), 50 percent of experts believe it is needed for both research and pilot projects, 37 percent believe that it is needed only for research, and a few feel that it is not needed. Thus, there is overwhelming support for national policy to regulate and govern SG research. However, no questions were asked to elicit responses on what the components of a national policy should be, since this is beyond the scope of the present research.

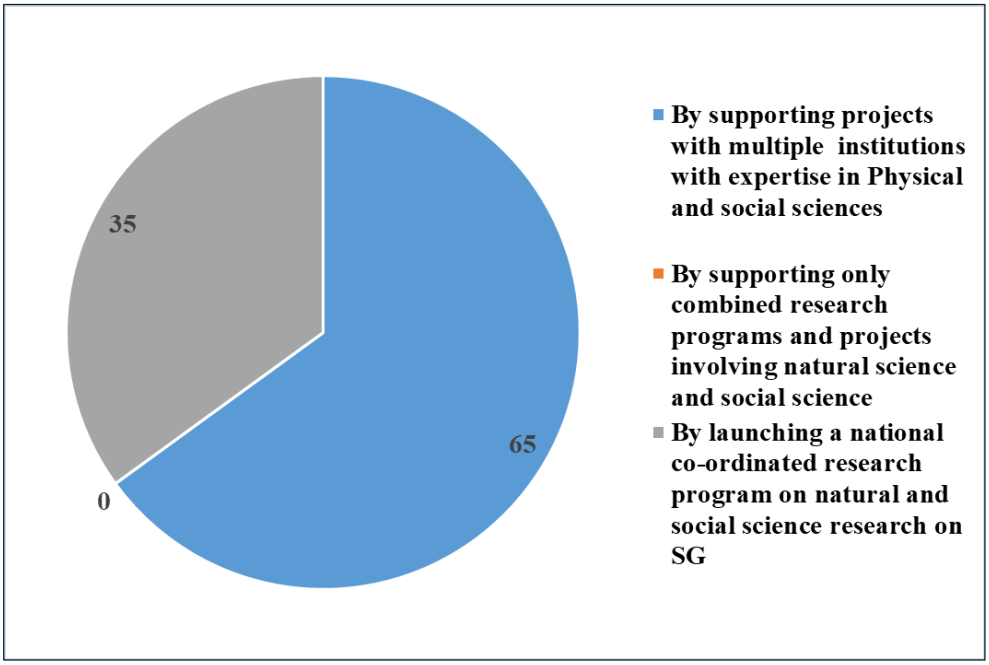
Figure 3. Need for a national policy on SG research on India (percent)



2.6. Strategy to Enhance SG Research

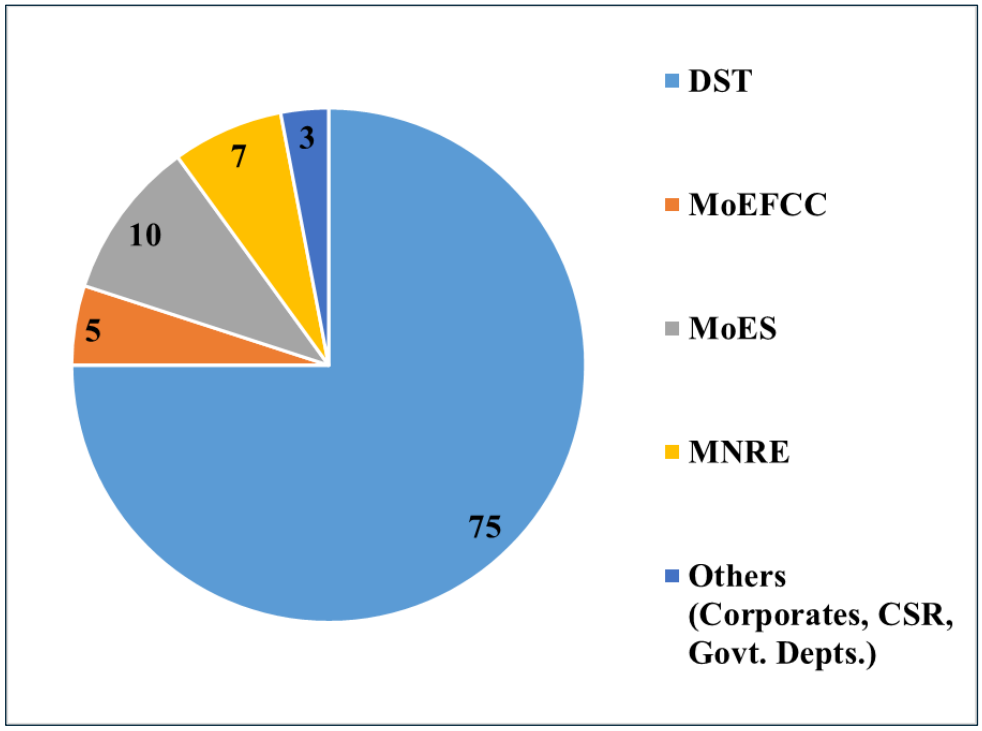
Promotion of integrated natural science and social science research (Figure 4): A majority (65 percent) of respondents suggest that projects involving multiple institutions with expertise on both natural and social science research should be supported. A third highlight a need for a nationally coordinated program involving both natural and social science research.

Figure 4. Promotion of integrated natural science and social science research on SG (percent)



Potential sources of financial support (Figure 5): Most of the experts suggest that DST should be the dominant funding agency, followed by the Ministry of Environment, Forest and Climate Change and Ministry of Earth Sciences, and some suggest that the funding could also come from corporations under the Corporate Social Responsibility scheme. Furthermore, the majority of respondents suggest that support should be largely from government departments, with a minority suggesting corporations and other sources.

Figure 5: Potential sources of financial support for SG research in India (percent)



International collaborations on SG research: The majority (70 percent) of respondents support promoting collaborative research involving Indian research institutions and foreign governments and donors (Figure 6a). About a third support only collaboration with international institutions/universities. There is overall support for collaborative research with external research institutions. Furthermore, the majority support external or international funding (from universities, bilateral funding agencies, such as British, Swedish, or German aid agencies, UN agencies, and research foundations) (Figure 6b). Only a fifth of respondents are not in favor of international funding.

Figure 6a. International collaborations on SG research (percent)

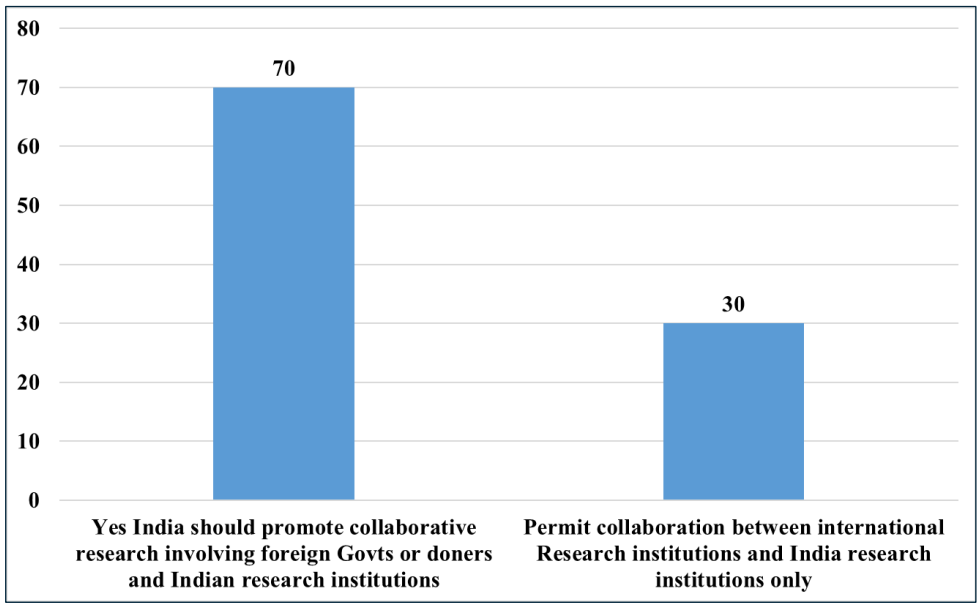
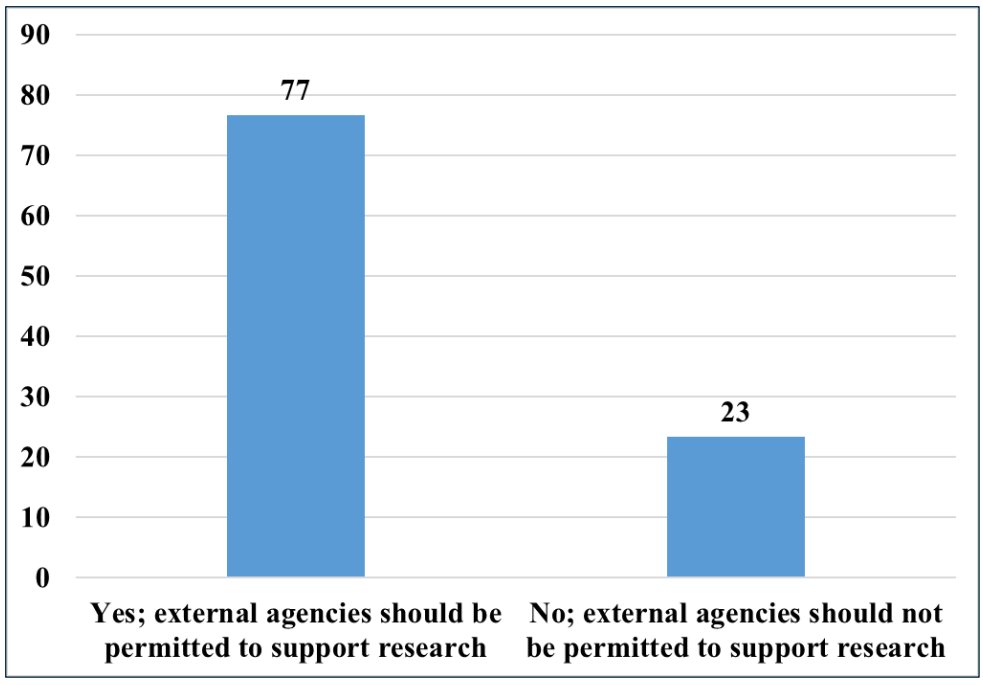
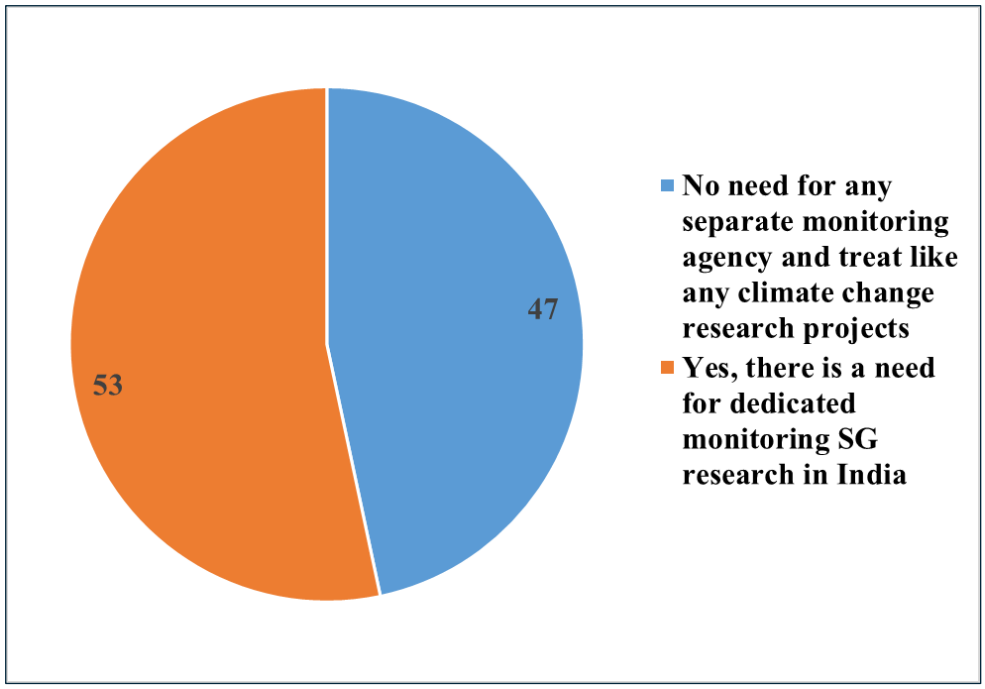


Figure 6b. International agencies to support SG research (percent)



Monitoring and regulation (Figure 7): About half of the experts indicate a need for dedicated monitoring. The remainder feel that this is not needed and that SG research should be treated as research on climate change.

Figure 7. Monitoring and regulation of SG research in India (percent)



Department or mechanism for monitoring and regulation (Figure 8a): Most respondents suggest that one of the government departments or a multidepartment (multiministerial) committee should monitor and regulate SG research, favoring DST.

Public disclosure and transparency (Figure 8b): The majority of respondents support the idea that SG research should be public knowledge and a dedicated website is required to publicize it and its findings. A designated government agency could manage such a system. About a fifth of respondents suggest that only pilot projects should be subjected to public disclosure. Some also feel that SG research should be treated as climate change research.

Figure 8a. Department or mechanism for monitoring and regulation of SG research (percent)

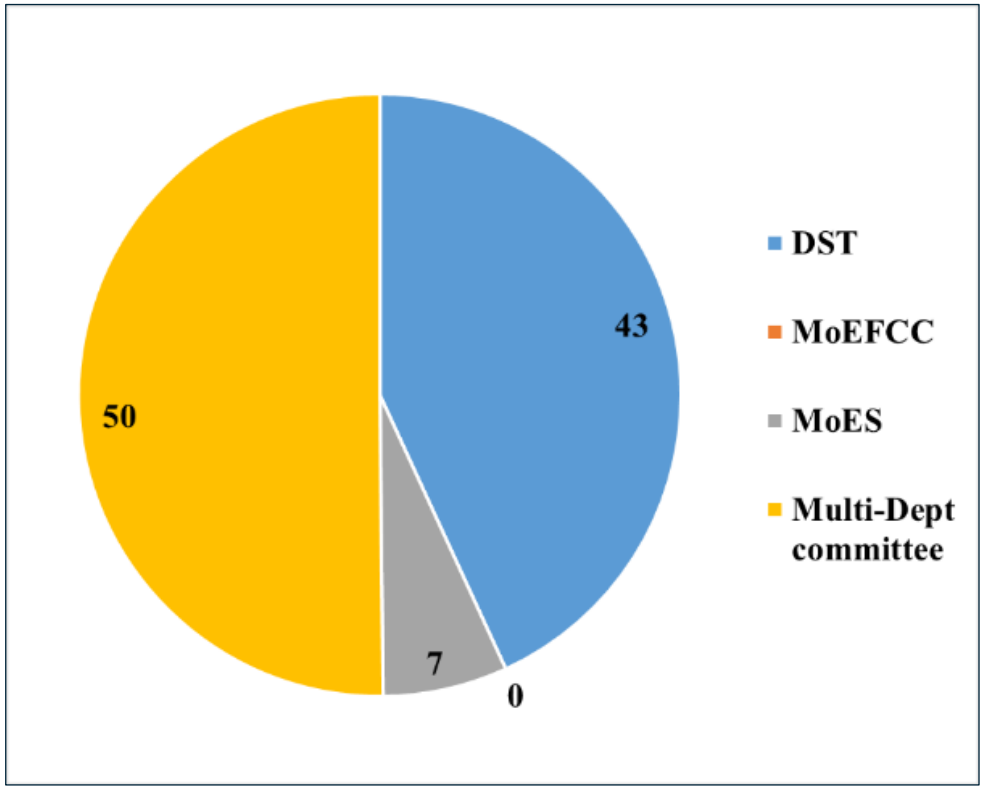
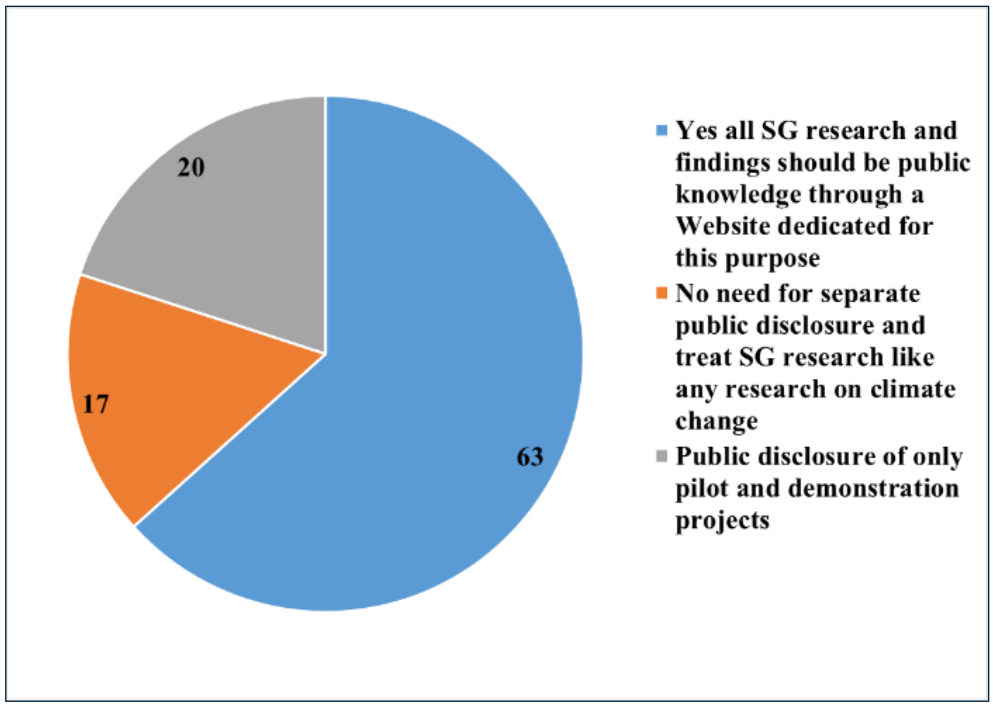
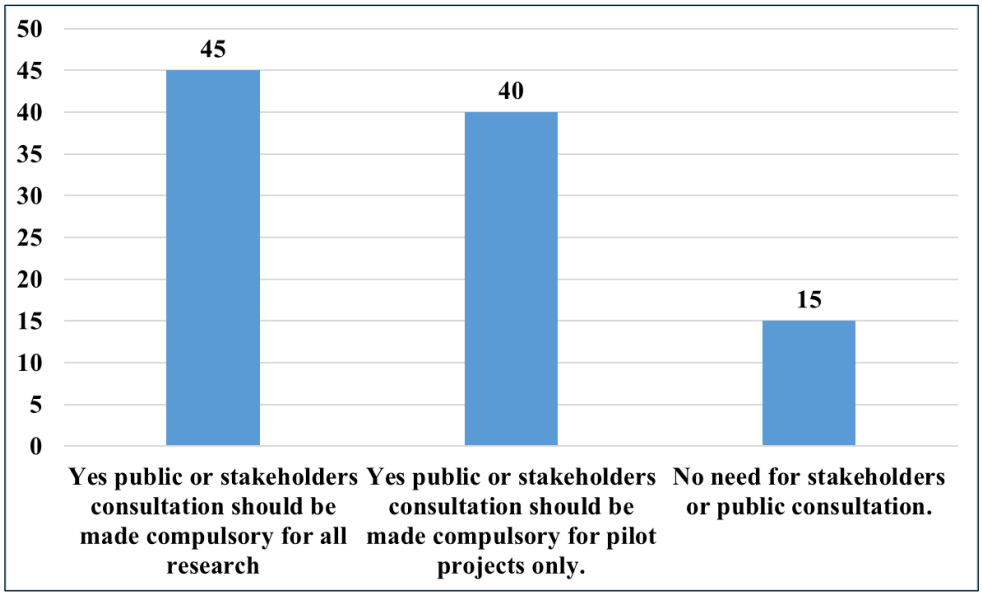


Figure 8b: Public disclosure and transparency of SG research (percent)



Stakeholder consultation for pilot projects (Figure 9): Most respondents agree on the need for stakeholder consultation, with about half of them suggesting that it should be mandatory, especially for pilot projects. Overall, there is support for public consultations on SG research in general and for pilot projects in particular.

Figure 9. Stakeholder consultation for pilot projects (percent)



2.7. Priority Research Areas

Expert opinion was also sought to identify the priority areas or topics for SG research in India. According to the expert survey, climate modeling is the most prioritized area, followed by small-scale field experiments and risk and impact analysis. A few experts identify technology development, and cost analysis is a third prioritized area, along with research on climate policy implications and on legal, political, ethical, and moral aspects. Other areas were included but at lower priority. Research on social science aspects is a low-priority area. Apart from governance, no other social science aspect of SG has received much attention globally, as a governance framework is deemed essential for pilot projects and large-scale deployment. Table 3 provides the details of the priority areas of the survey for different research themes.

Table 3. Priority areas for SG research in India

Research themes	Priority 1	Priority 2	Priority 3	Priority 4	Priority 5
1. Climate modeling	16	5			1
2. Small-scale field experiments	1	10	4	2	2
3. Technology development, engineering, and cost analysis	1	2	5	5	2
4. Risk and impact analysis of SG	5	9	6	7	1
5. Climate policy implications		3	6	2	6
6. Legal, political, ethical, and moral aspects	2	1	2	6	1
7. Governance aspects		1	1	1	3
8. Research on social science aspects	2		1	3	1
9. Research on the national and international governance of SG		1	1	1	3
10. All aspects of SG	2		1		

2.8. Implications of SG Research on Climate Change Mitigation and Adaptation

The global opinion is that any research on SG could impact mitigation and adaptation efforts. Our survey highlighted the following:

- The majority of respondents (77 percent) believe that if SG research is considered as a potential solution, it could weaken mitigation and adaptation efforts.

- About a fifth (23 percent) considered SG a very risky strategy and suggested that we should continue to focus on mitigation and adaptation efforts.

3. Discussion

This section includes a discussion of the implications of findings of the literature review and questionnaire on the need for a national policy, government funding, governance mechanisms, India's role in global SG research, and potential impacts on mitigation adaptation actions.

3.1. National Policy

A national policy and an international protocol are required to promote, regulate, and monitor SG research. Our survey reveals that the majority of respondents favor a national policy in India that would guide government ministries, corporations, philanthropists, and researchers and enable funding for SG research. Bala and Gupta (2019) also highlighted the need for a national framework. It should consider the following:

1. **Identify priority areas**: The national-level survey in this study shows that research priorities are as follows: climate modeling, risk assessments, technology development, and legal, political, and governance aspects. Social science research was a low priority according to the survey. However, given the potentially large socioeconomic implications, it is necessary to support interdisciplinary research. Having a national policy and a set of clearly identified priority areas could facilitate financial support from international agencies, corporations, and philanthropy.

2. **Regulation, transparency, public disclosure, and monitoring**: Given the uncertainties and risks involved in research and deployment, research areas need to be regulated by a national policy. Our opinion survey reveals that a majority of participants support the need for regulation, transparency, stakeholder consultation, public disclosure, and monitoring. As SG is a new and specialized area, relevant government ministries, elected representatives (such as mayors or parliamentarians), academic institutions, industry agencies, and civil society organizations could be involved in the initial discussion. It is to early to consult citizens due to limited understanding of SG at this stage. A regulatory framework, transparency, and public disclosure are very important, especially if corporations and philanthropists are involved in large-scale funding. The survey also reveals that a majority of respondents favor an interdepartmental (interministerial) committee coordinated by DST to monitor and regulate research. Several such interdepartmental committees on other domains exist, and their roles are usually determined by the coordinating department. The regulatory or monitoring agency should also extend to monitoring international, corporate, or philanthropy support.

3. **Social and natural science research**: The findings of the survey show limited overall research on SG in India and a further lack of appreciation for social science research. NASEM (2021) highlighted the importance of research on social dimensions, including research on public perceptions and engagements, effective governance, and integration of justice, ethics and equity considerations. Thus, India needs to make dedicated efforts to involve social scientists along with natural and physical scientists.

Aldy et al. (2021) highlight that disciplinary and interdisciplinary research should contribute to reducing the large uncertainties in the anticipated impacts of climate change, costs, and social aspects of techniques such as SG. All the risks and uncertainties of the technology must be understood and its deployment risks compared with risks arising out of unmitigated climate change leading to a warming beyond 2°C (Felgenhauer et al. 2022).

3.2. Government or Public Funding

The level of support from the Indian government for SG research provides an impetus or indication to facilitate funding from the corporations and philanthropies. The survey shows that a majority of respondents support government funding, especially from DST. Necheles et al. (2018) shows that, up to 2018, support for SG research is marginal, with government support dominating in Europe (USD 20 million) and Asia (USD 3 million) and private-sector funding dominating in North America (USD 18 million). Reynolds (2019) highlights that due to lack of government engagement, NGOs can play an important role. The UK policy is aimed at not deploying SG. However, the UK government has commissioned research into effects of SG on climate and monitors research (BEIS 2020). In the United States, NASEM (2021) recommended USD 100–200 million for a new five-year SG research program. The UK Meteorological Office and American Meteorological Society advocate for more research. DST has also been actively supporting a climate modeling SG program over the last five years under the broader climate change research program (Bala and Gupta 2019). Without a clear government policy, corporate and philanthropy support will be limited or nonexistent. Thus, the national policy should highlight the role of government and nongovernment actors.

3.3. Governance for Research

Given the risks and uncertainties associated with SG research and its implications for deployment, there is a general agreement on the need for research governance. NASEM (2021) recommends that research should operate under robust governance, support development of an international governance mechanism, and include a code of conduct, a public registry, a regular program assessment and review process, permit systems for outdoor experiments, guidance on intellectual property, inclusive public and stakeholder engagement processes, mechanisms for advancing international information sharing and collaborations, and an expert committee on

international governance needs and strategies. However, no overarching global environmental agreement governs SG (Bhasin et al. 2022). Bhasin et al. (2022) also emphasize the centrality of transparency as a governance principle for SG research. In our survey, the majority of respondents support the idea of mandatory public disclosure and stakeholder consultation of all projects and further monitoring and supervision by a government agency, such as DST. Aldy et al. (2021) highlight that research support for SG would require transdisciplinary processes involving stakeholders from scientific and policy communities, civil society, and the public, especially in making decisions on a large-scale program. Keith and Irvine (2021) also emphasize the need for robust scientific scrutiny, multilateral collaborations, and transparent discussions about governance.

Long and Parson (2018) propose that research governance needs can be grouped into three basic functions: **1. enable reliable research**: provide the authorization, resources and management necessary for research to proceed, in conjunction with guidance and quality controls to help ensure that results are useful and relevant to inform societal choices; **2. legitimize research**: ensure that topics, methods, and conduct are compatible with basic moral, democratic, and legal principles and broadly acceptable to relevant citizens; and **3. control research impacts**: ensure that potential harms or risks are recognized and appropriately managed.

There is also a need for promoting international partnership and collaboration in SG research. In our survey, most respondents supported international collaborations, particularly those funded by the governments. NASEM (2021) and Rahman et al. (2018) also highlight the need for promoting international partnerships and collaboration, which should include countries that have been underrepresented in global decisionmaking.

3.4. Role for India in SG Research

As a large developing country, with bulk of the population depending on climate-sensitive sectors (such as agriculture, horticulture, fishing, and forestry) for its livelihood, India is one of the most vulnerable countries in the world to climate change risks. India shares a large border with many countries, including China. Given the potential for transboundary impacts of any large-scale SG interventions, India should undertake research on all aspects of SG and develop mitigation measures. Rahman et al. (2018) concludes that developing countries must lead research on SG and collaborate with local scientists to conduct research that is sensitive to regional concerns. They highlight that politically and morally, the Global South should have a central role in SG research, evaluation, and discussion. Bala and Gupta (2019) emphasize that most SG research is conducted in the developed world, with very little research or discussion taking place in the Global South, and the developing countries should have a central role in research, discussion, and evaluation for political and

moral reasons. India, as a leading scientific power among the developing nations, should take the lead in SG research. India has shown similar leadership recently through “International Solar Alliance,” “One Sun One World One Grid,” and “Coalition for Disaster Resilient Infrastructure.”

3.5. SG Research and Climate Change Mitigation and Adaptation Actions

Many fear that any serious progress on SG research could potentially delay or halt global efforts on mitigation and adaptation activities. Keith and Irvine (2021) highlight that if SG becomes recognized as an effective means of reducing climate change, then it may reduce societal willingness to make the difficult transition to a net zero world. The more effective and convenient SG seems to be, the greater the potential threat to a net zero world. Aldy et al. (2021), based on current knowledge, highlight that climate SG techniques cannot be relied on to significantly contribute to meeting the Paris Agreement temperature goals. Reynolds (2019) mentions the concern that SG would harmfully lessen abatement of GHG emissions, but what can be done to reduce such displacement remains unclear. Khabbazan et al. (2020) considers multiple temperature targets and concludes that for climate change larger than 4°C, SG will be an unavoidable policy tool to comply with the temperature targets.

4. Conclusions

We identify that there is very limited research on SG in India, in particular on the social science and interdisciplinary aspects. The Indian scientific community has overall support for increasing research. Scientific research must continue, and the Global South, including India, should be actively engaged in SG research, evaluation, and discussion. Based on our literature review and survey results, we see a strong argument that India should also continue to engage in scientific research on SG, while its policy on the issue may be evolving. The way forward in a large country could include the following elements:

1. To avoid lagging behind in this area, the government should formulate a national SG research policy that promoting interdisciplinary research including both natural and social science aspects, focusing more on modeling, risk and impact assessments, and policy analysis. Awareness must be created on the need for interdisciplinary research on SG, including both natural and social science aspects, given the very limited awareness on the importance of the social science aspects of SG. A comprehensive discussion on the development of a national policy is beyond the scope of this paper, as it requires stakeholder consultations that would include government departments, industry, civil society, and the scientific community. We believe that the DST is better positioned to constitute an expert body to initiate discussion on a potential national policy that could guide research, governance, pilot project implementation, etc.
2. To ensure that the public interest is reflected, the government should be the dominant funding agency for R&D on SG and formulate a policy to encourage international collaborations along with external funding, in particular from government sources.
3. Public consultation, disclosure, and transparency on research and monitoring by an interdepartmental committee is required to ensure regulation. Along with a national regulatory mechanism, robust international research governance and framework are required.
4. The research community and other stakeholders overall support R&D under the ambit of a national policy on SG research in India and an international research governance and framework.

5. References

Aldy, Joseph E., Tyler Felgenhauer, William A. Pizer, Massimo Tavoni, Mariia Belaia, Mark E. Borsuk, Arunabha Ghosh, et al., 2021. Social Science Research to Inform Solar Geoengineering. *Science* 374(6569): 815–18.

Bala, G., and Akhilesh Gupta. 2019. "Solar geoengineering research in India," *Bulletin of the American Meteorological Society*: 23–28. [doi: 10.1175/BAMS-D-18-0122.1]

Bala, G., and Akhilesh Gupta, 2017. Geoengineering and India, Meeting Report. *Current Science* 113(3), 376–7.

Bala, G., and Akhilesh Gupta. 2018. "India forges ahead with solar-geoengineering studies," *Nature Correspondence* **557**, 637. [doi: 10.1038/d41586-018-05288-6]

Bala, G., K. Caldeira, R. Nemani, L. Cao, G. Ban-Weiss, and H.J. Shin. 2010b. Albedo Enhancement of Marine Clouds to Counteract Global Warming: Impacts on the Hydrological Cycle. *Climate Dynamics* 37: 915–31. [doi: 10.1007/s00382-010-0868-1]

Bala, G., K.S. Krishnamohan, and Akhilesh Gupta. 2019. Solar Geoengineering Research Activities in India. *The Journal of Governance* 18 (Special edition on environment): 264–72

Bala, G., and B. Nag. 2011. "Albedo enhancement over land to counteract global warming: Impacts on hydrological cycle," *Climate Dynamics* [doi: 10.1007/s00382-011-1256-1]

BEIS (Business, Energy and Industrial Strategy). 2020. *The UK Government's View on Greenhouse Gas Removal Technologies and Solar Radiation Management*. Department for Business, Energy and Industrial Strategy.

Bhasin, S., B. Ravindran, and E. Moro. 2022. *Solar Geoengineering and the Montreal Protocol, A Case Study of Global Governance*. CEEW.

Eckstein, D., V. Kunzel, and L. Schafer. 2021. Global Climate Risk Index 2021. [doi: 978-3-943704-84-6]

Felgenhauer, T., G. Bala, M. Borsuk, M. Brune, I. Camilloni, J.B. Wiener, and J. Xu. 2022. *Solar Radiation Modification: A Risk–Risk Analysis*. New York, NY: Carnegie Climate Governance Initiative. **www.c2g2.net**

IPCC (Intergovernmental Panel on Climate Change). 2021. Climate Change 2021: The Physical Science Basis. In *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* edited by V. Masson-Delmotte, P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou. Cambridge, UK and New York, NY, USA: Cambridge University Press. [doi: 10.1017/9781009157896]

IPCC. 2022. *Technical Summary, IPCC WGII Sixth Assessment Report*.

Kalidindi, S., G. Bala, A. Modak, and K. Caldeira. 2014. "Modeling of solar radiation management: A comparison of simulations using reduced solar constant and stratospheric sulphate aerosols," *Climate Dynamics* 44: 2909–25 [doi: 10.1007/s00382-014-2240-3]

Keith, David, and P. Irvine. 2021. The US can't go it alone on solar geoengineering. **https://policyexchange.org.uk/the-us-cant-go-it-alone-on-solar-geoengineering/**

Khabbazan, M.M., M. Stankoweit, E. Roshan, H. Schmidt, and H. Held H. 2021. "How can solar geoengineering and mitigation be combined under climate targets?" *Earth System Dynamics* 12(4): 1529–42. [**https://doi.org/10.5194/esd-12-1529-2021**]

Krishnamohan, K.S., and G. Bala. 2022. "Sensitivity of tropical monsoon precipitation to the latitude of stratospheric aerosol injections." *Climate Dynamics* 59: 151–68. **https://doi.org/10.1007/s00382-021-06121-z**

Krishnamohan, K.S., G. Bala, Long Cao, Lei Duan, and Ken Caldiera. 2019. "Climate system response to stratospheric sulfate aerosols: Sensitivity to altitude of aerosol layer," *Earth System Dynamics Discussion* 8(2): e2019EF001326. **https://doi.org/10.5194/esd-2019-21**

Krishnamohan, K.S., G. Bala, Long Cao, Lei Duan, and Ken Caldiera. 2020. "The climatic effects of hygroscopic growth of sulfate aerosols in the stratosphere." *Earth's Future* **https://doi.org/10.1029/2019EF001326**

Lenton, A., Boyd, P.W., Thatcher, M., et al. 2019. "Foresight must guide geoengineering research and development," *Nature Climate Change* 9(342). **https://doi.org/10.1038/s41558-019-0467-z**

Long, J., and E. Parson. 2019. Functions of Geoengineering Research Governance. UCLA: School of Law. **https://escholarship.org/uc/item/54c158tt**

MacMartin, Douglas M.G., K.L.R. Ricke, and David W. Keith. 2018. "Solar geoengineering as part of an overall strategy for meeting the 1.5°C Paris target," *Philosophical Transactions of the Royal Society A* 376(2119). **https://doi.org/10.1098/rsta.2016.0454**

Modak, A., and G. Bala. 2014. Sensitivity of Simulated Climate to Latitudinal Distribution of Solar Insolation Reduction in Solar Radiation Management. *Atmospheric Chemistry and Physics* 14: 7769–79.

Muthyala, R., G. Bala, and A. Nalam. 2018a. Regional Scale Analysis of Climate Extremes in an SRM Geoengineering Simulation, Part 1: Precipitation Extremes. *Current Science* 114(5): 1024–35.

Muthyala, R., G. Bala, and A. Nalam. 2018b. Regional Scale Analysis of Climate Extremes in an SRM Geoengineering Simulation, Part 2: Temperature Extremes. *Current Science* 114(5): 1036–45.

Nalam, A., G. Bala, and A. Modak. 2018. "Effects of Arctic geoengineering on tropical precipitation," *Climate Dynamics* 50: 3375–95. [doi: 10.1007/s00382-017-3810-y]

NASEM (National Academies of Sciences, Engineering, and Medicine). 2021. *Reflecting Sunlight: Recommendations for Solar Geoengineering Research and Research Governance*. Washington, DC: National Academies of Sciences, Engineering, and Medicine.

Necheles, E., L. Burns, A. Chang, and David Keith. 2018. Funding for solar geoengineering from 2008 to 2018. **https://geoengineering.environment.harvard.edu/blog/funding-solar-geoengineering**

Rahman, A., P. Artaxo, A. Asrat, and A. Parker. 2018. Developing Countries Must Lead on Solar Geoengineering Research. *Nature* 556: 1476–687.

Reynolds, J.L. 2019. “Solar geoengineering to reduce climate change: A review of governance proposals,” *Proceedings of the Royal Society A* 475(2229). **http://doi.org/10.1098/rspa.2019.0255**

Singh, Jyoti, Sandeep Sahany, and Alan Robock. 2020. Can Stratospheric Geoengineering Alleviate Global Warming–Induced Changes in Deciduous Fruit Cultivation? The Case of Himachal Pradesh (India). *Climatic Change* 162: 1323–43.

State of the Global Climate. 2021. WMO No. 1290, [doi: 978-92-63-11290-3]

Yang, Huiyi, Steven Dobbie, Julian Ramirez-Villegas, Kuishuang Feng, Andrew J. Challinor, Bing Chen, Yao Gao, Lindsay Lee, Yan Yin, Laixiang Sun, James Watson, Ann-Kristin Koehler, Tingting Fan, and Sat Ghosh. 2016. Potential Negative Consequences of Geoengineering on Crop Production: A Study of Indian Groundnut. *Geophysical Research Letters* 43: 11786–95.